MICROSTRIP LOSS

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THESIS

MICROSTRIP LOSS

by

Remzi Arikonmaz

December 1975

Thesis Advisor: Jeffrey B. Knorr

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Microstrip Loss

by

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Submitted in partial fulfillment of the
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I. INTRODUCTION

Microstrip is a transmission line structure which has enjoyed widespread use in microwave integrated circuitry [Ref. 1]. It has been analyzed by many investigators. The analyses range from the early quasi-static approaches to the more recently published frequency dependent analysis. One frequency dependent analysis technique which has been proven accurate, versatile and efficient is the spectral domain technique [Ref. 2], [Ref. 3]. This technique has been applied to the determination of wavelength and impedance for both single and coupled microstrips [Ref. 2].

To fully characterize the circuit behaviour of microstrip, it is necessary to evaluate the losses as well as the wavelength and characteristic impedance. Past analyses of loss [Ref. 1], [Ref. 4] have been based upon quasi-static formulations, however. It is natural, therefore, to extend the spectral domain technique to calculate loss and thereby properly account for frequency dependence of the field configuration as well as the surface resistance.

This thesis presents a spectral domain analysis of microstrip losses. In the remainder of this chapter, section A reviews and summarizes the spectral domain formulation of characteristic impedance and wavelength which is treated in detail in [Ref. 6]. Section B reviews previous studies of microstrip loss and section C details the purpose of the present

work. Chapter II presents the results of the theoretical analysis which is described in detail in the appendices. Chapter III describes the computer program implementation and finally, results and conclusions are presented in Chapter IV.

A. SPECTRAL DOMAIN APPROACH TO Z_o AND λ'

The microstrip field is expressed as a linear combination of TE and TM modes characterized by

$$E_{zi}\,(x,y,z) = k_{ci}^2 \phi_i^e(x,y)\; e^{z} \tag{1a}$$

$$H_{xi}\,(x,y,z) = k_{ci}^2\; \phi_i^h\,(x,y)\; e^{z} \tag{1b}$$

where $k_{ci}^2 = \gamma^2 + k_i^2$, is the propagation constant, i denotes the appropriate region and ϕ_i are unknown scalar potential functions.

Applying boundary conditions at the interfaces between the two regions, at y=0 and y=D leads to a set of boundary equations. Although the ϕ_i are unknown, their Fourier transforms $\Phi_i\,(\alpha,y)$, with respect to x, can be found. Thus, the boundary equations are transformed and the general solutions for the $\Phi_i(\alpha,y)$ are substituted. Extensive algebraic manipulations of the resulting equations leads to the coupled set,

$$\mathcal{E}_x(\alpha) = G_1(\alpha,\beta)\; J_x\,(\alpha) + G_2\,(\alpha,\beta)\; J_z\,(\alpha) \tag{2a}$$

$$\mathcal{E}_z(\alpha) = G_3(\alpha,\beta)\; J_x\,(\alpha) + G_4\,(\alpha,\beta)\; J_z\,(\alpha) \tag{2b}$$

where $\mathcal{E}_i(\alpha)$ and $J_i(\alpha)$ are the transforms of the electric field and the surface current at $y = D$, and   is the transform variable.

Since the conductor is sufficiently narrow, it can be assumed, transverse current density $J_x(\alpha)$ is zero. Thus,

$$G_2(\alpha, \beta)\, J_z(\alpha) = \mathcal{E}_x(\alpha) \tag{3a}$$

$$G_4(\alpha, \beta)\, J_z(\alpha) = \mathcal{E}_z(\alpha) \tag{3b}$$

Next, define an inner product as,

$$\langle A(\alpha), B(\alpha) \rangle = \int_{-\infty}^{+\infty} A(\alpha)\, B^*(\alpha)\, d\alpha . \tag{4}$$

The complex conjugate of $J_z(\alpha)$ can be chosen as a suitable weighing function $W(\alpha)$.

Taking the inner product of equation (3b) with $W(\alpha)$, then, applying Parseval's theorem, the right-hand side of the equation (3b) becomes zero because of the orthogonality of $\mathcal{E}_z(\alpha)$ and $J_z(\alpha)$.

Thus, one can obtain the final form of the equation (3b) as,

$$\int_{-\infty}^{+\infty} G_4(\alpha, \lambda/\lambda')\, \left| J_z(\alpha) \right|^2 d\alpha = 0 \tag{5}$$

Therefore, phase velocity characteristics of microstrip can be determined by finding those values of the propagation

constant that give a zero value for the integral at a particular frequency.

The spectral domain technique can also be extended to obtain characteristic impedance of the microstrip.

Assuming transverse current is zero, define characteristic impedance as

$$Z_o = \frac{2P_{avg}}{I_{oz}^2} \tag{6}$$

for a single strip.

The average power is calculated as

$$P_{avg} = \frac{1}{2} \mathrm{Re} \iint (E_x H_y^* - E_y H_x^*) \, dx \, dy \tag{7}$$

where the transverse fields may be found from equations (1a) and (1b) in terms of the unknown scalar potential functions ϕ_i (x,y). However, Parseval's theorem may be applied to obtain

$$P_{avg} = \frac{1}{4\pi} \mathrm{Re} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \Big[\mathcal{E}_x(\alpha, y) \mathcal{H}_y^*(\alpha, y) - \mathcal{E}_y(\alpha, y) \mathcal{H}_x^*(\alpha, y)\Big] \, d\alpha \, dy \tag{8}$$

where the script quantities denote the transforms of the fields and are given in terms of the Φ_i (α, y). At this point, the general solutions for the $\Phi_i(\alpha, y)$ may be substituted and the integration with respect to y, can be

accomplished analytically. This leaves an equation of the form,

$$P_{avg} = \frac{1}{4\pi} \int_{-\infty}^{+\infty} G(\alpha)\, d\alpha \qquad (9)$$

which is evaluated numerically in each of the two regions. Thus, the characteristic impedance may be found by substituting the result of equation (9) and the axial current component, into equation (6).

B. PREVIOUS STUDIES OF MICROSTRIP LOSS

Microstrip loss has been studied by several investigators. One method, introduced by Mittra and Itoh [Ref. 1], assumes the dominant mode of the microstrip is quasi-TEM. With regard to this assumption, the following formulas may be written for the two components of the attenuation constant,

$$\alpha_d = \iint \sigma_d \,(\nabla\phi)^2\, dx\, dy \Big/ \left[2 \iint v\epsilon\, (\nabla\phi)^2\, dx\, dy\right] \qquad (10a)$$

$$\alpha_c = R_s\, I_s^2\, dl \Big/ \left[2 \iint v\epsilon\, (\nabla\phi)^2\, dx\, dy\right] \qquad (10b)$$

$$I_s = \rho_s \cdot v \qquad (10c)$$

where ϕ is the potential distribution, v is the phase velocity, ρ_s is charge distribution on the conductors, R_s is surface resistance and σ_d is conductivity of dielectric material.

The double integrals are defined over the cross-section of the microstrip, the line integral is taken around the center strip and along the ground conductor surface.

The quantities ϕ, ρ_s and v in equation (10) can be calculated either using the "Modified Conformal Mapping Method" introduced by Wheeler [Ref. 5] or using other techniques described in [Ref. 1].

Another approach for calculation of losses in microstrip has been used by Pucel [Ref. 4] who has developed formulas that express conductor and dielectric losses in terms of physical parameters of the microstrip and the "Filling Factor" introduced by Wheeler [Ref. 5].

According to Pucel, dielectric loss is given by

$$\alpha_d \approx 4.34 \frac{q}{\sqrt{K_e}} \sqrt{\frac{\mu_o}{\epsilon_o}}\, \sigma \quad \text{dB/cm.} \tag{11}$$

where K_e is the effective dielectric constant of the substrate defined as $K_e = 1 + q\,(K-1)$ and q is the filling factor defined by Wheeler.

To obtain the ohmic attenuation constant α_c, Pucel used a technique based on the so-called "Incremental inductance rule" which is also due to Wheeler. This rule expresses the surface resistance R_s per unit length, in terms of that part of the total inductance per unit length which is attributable to the skin effect; that is, the inductance produced by the magnetic field within the conductors.

It is well known that the surface impedance

$$Z_s = R_s + jX_s$$

has a real part R_s which is equal to the imaginary part X_s, where

$$X_s = \omega L_i$$

According to Wheeler, L_i can be inferred from the external inductance L per unit length, as the incremental increase in L , caused by an incremental recession of all metallic walls carrying a skin current. The amount of recession is equal to half the skin depth,

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \qquad (12)$$

An assumption, underlying this rule is that the radius of curvature and the thickness of the conductors exposed to the electric field be greater than the skin depth.

Using Wheeler's incremental inductance and surface resistance formulas, equation (112) in [Ref. 1] and assuming that the inductance per unit length for the microstrip line is approximately the same as that of the unloaded TEM line, Ohmic attenuation constant expressions are obtained for three different w/h ratios as

$$\frac{\alpha_c Zh}{R_s} = \frac{8.64}{2\pi} \left[1 - \left(\frac{w'}{4h}\right)^2\right] \qquad (13a)$$

$$\times \left(1 + \frac{h}{w'} + \frac{h}{\pi w'}\left[\ln\left(\frac{4\pi w}{t} + 1\right)\right.\right.$$

$$\left.\left. - \frac{1 - t/w}{1 + t/4\pi w}\right]\right) \quad w/h \leqslant 1/2$$

$$\frac{\alpha_c Zh}{R_s} = \frac{8.64}{2\pi} \left[1 - \left(\frac{w'}{2 \times 2h}\right)^2\right] \qquad (13b)$$

$$\times \left(1 + \frac{h}{w'} + \frac{h}{\pi w'}\left[\ln\left(\frac{2h}{t}\right) + 1\right.\right.$$

$$\left.\left. - \frac{1 + t/h}{1 + t/2h}\right]\right) \quad 1/2 < w/h \leqslant 2$$

$$\frac{\alpha_c Zh}{R_s} = \frac{8.68}{(w/h) + (2/\pi)\ln\left(2\pi e\,|(w'/2h) + 0.94|\right)} \qquad (13c)$$

$$\times \left[\frac{w'}{h} + \frac{w'/\pi h}{w'/2h + 0.94}\right]$$

$$\times \left(1 + \frac{h}{w'} + \frac{h}{\pi w'}\left[\ln\frac{2h}{t} + 1\right.\right.$$

$$\left.\left. - \frac{1 + t/h}{1 + t/2h}\right]\right) \quad w/h > 2$$

where $w' = w + \Delta w$ and w is defined as

$$\Delta w = \frac{t}{\pi} \ln\left(\frac{4\pi w}{t} + 1\right) \quad w/h \;\; 1/2 \qquad (14a)$$

$$\Delta w = \frac{t}{\pi} \ln \left(\frac{2h}{t} + 1 \right) \qquad w/h \geq 1/2 \qquad (14b)$$

C. PURPOSE OF THE WORK

The analysis of microstrip is of great importance as this type of transmission line has found wide use due to its compatibility with microwave integrated circuitry.

For design purposes, it is necessary to know how the characteristic impedance, the phase velocity and the attenuation constant of the dominant microstrip mode depend on physical parameters, on electromagnetic properties of the substrate and conductors, and on the frequency.

The spectral domain approach to computation of characteristic impedance and phase velocity of the microstrip lines has been introduced in [Ref. 6].

Microstrip loss is of concern, as described in Chapter 1-B. Mittra and Itoh's method assumes the dominant mode of microstrip is quasi-TEM. It can be easily proven that inhomogeneous guidance structures cannot support a TEM mode. Although microstrip line has an inhomogeneous cross section, quasi-TEM mode approximation can be used, since most of the fields are confined between the two conductors. However, this approximation is only valid for frequencies up to 5 GHz [Ref. 3].

On the other hand, Pucel's method is based on the so-called "incremental inductance rule" which used approximations in the derivation of the inductance itself.

For this reason, the spectral domain approach for calculation of microstrip loss has been introduced here.

Due to the limitations of the previous studies of microstrip loss the study described here was undertaken. This study treats both dielectric and conductor loss using the hybrid field analysis described in section-A of this chapter.

II. THEORETICAL ANALYSIS

Assume total loss per unit length in the microstrip to be small. The line loss can then be quantitatively described in terms of the attenuation constant defined as,

$$\alpha = - \frac{dP/dz}{2P(z)} \quad . \tag{15}$$

Power loss per unit length for the center conductor is

$$- \frac{dP}{dz} = \frac{1}{2} \oint_c R_s \quad |J_s|^2 \quad .dl \tag{16}$$

where R_s is the surface resistance and J_s is the surface current density and

$$\bar{J}_s = \bar{n} \times \bar{H}_{tan.} \tag{17}$$

$$R_s = \sqrt{\frac{\omega \mu}{2 \sigma}} \quad . \tag{18}$$

Substituting equation (17) into equation (16), one obtain

$$\frac{dP}{dz} = - \frac{R_s}{2} \oint_c \left| H_{tan.} \right|^2 \quad dl. \tag{19}$$

Because of the finite width of the center conductor, Parseval's theorem cannot be applied to equation (19)

directly. To overcome this difficulty, a function f(x) can be generated which defined as,

$$f(x) = \begin{cases} 1 & -w/2 \leqslant x \leqslant w/2 \\ 0 & \text{elsewhere} \end{cases} \tag{20}$$

Tangential magnetic field can be multiplied by f(x) without disturbing the field. Then equation (19) becomes

$$-\frac{dP}{dz} = \frac{R_s}{2} \int_{-\infty}^{+\infty} f(x) \left| \bar{H}_{tan.} \right|^2 \cdot dl \tag{21}$$

Substituting field expressions into equation (21), applying Parseval's theorem and evaluating transformed scalar potential functions at y=D, as done in Appendix A, the attenuation constant of the center conductor is obtain as

$$\alpha_c = \frac{R_s}{2P_{avg}} \left(\frac{1}{2\pi}\right)^2 \iint_{\substack{-\infty \\ \text{HYP.} \\ \text{REG.}}}^{+\infty} \left[\beta\alpha \overset{*}{A}{}^h - j\omega\epsilon_1 \gamma_1 \overset{*}{A}{}^e\right] w$$

$$\left[\frac{\operatorname{Sin}(\alpha - \rho)\, \frac{w}{2}}{(\alpha - \rho)\, \frac{w}{2}}\right]$$

$$\left[-\beta\alpha A^h(\rho) + j\omega\epsilon_1 \gamma_1\, A^e(\rho)\right] d\rho\, d\alpha + \frac{R_s}{2P_{avg}} \left(\frac{1}{2\pi}\right)^2$$

$$\iint_{\substack{-\infty \\ \text{HYP.} \\ \text{REG.}}}^{+\infty} \left[\beta\alpha \overset{*}{C}{}^h_H(\alpha)\, \operatorname{Cosh} \gamma_2 D + j\omega\epsilon_2 \gamma_2\, \overset{*}{B}{}^e_H(\alpha)\, \operatorname{Cosh} \gamma_2 D\right]$$

$$w\left[\frac{\operatorname{Sin}(\alpha-\rho)\frac{w}{2}}{(\alpha-\rho)\frac{w}{2}}\right]\left[-\beta\alpha C_H^h(\rho)\operatorname{Cosh}\gamma_2 D\right.$$

$$\left.-j\omega\epsilon_2\gamma_2 B_H^e(\rho)\operatorname{Cosh}\gamma_2 D\right]$$

$$d\rho\, d\alpha+\frac{R_s}{2P_{avg}}\iint_{\substack{\text{TRIG.}\\ \text{REG.}}}{}_{-\infty}^{+\infty}\left[\beta\alpha\overset{*}{C}{}_T^h(\alpha)\operatorname{Cos}\gamma_2'' D\right.$$

$$\left.+\omega\epsilon_2\gamma_2''\overset{*}{B}{}_T^e(\alpha)\operatorname{Cos}\gamma_2'' D\right]$$

$$w\left[\frac{\operatorname{Sin}(\alpha-\rho)\frac{w}{2}}{(\alpha-\rho)\frac{w}{2}}\right]\left[\beta\alpha C_T^h(\rho)\operatorname{Cos}\gamma_2'' D\right.$$

$$\left.+\omega\epsilon_2\gamma_2'' B_T^e(\rho)\operatorname{Cos}\gamma_2'' D\right]d\rho\, d\alpha\,. \qquad (22)$$

The ground plane attenuation constant may be found by substituting field expressions into equation (19), applying Parseval's theorem and evaluating transformed scalar potential functions at y=0 (see Appendix A) as

$$\alpha_g=\frac{R_s}{2P_{avg}}\frac{1}{2\pi}\int_{\substack{\text{HYP.}\\ \text{REG.}}}\left(\left[k_{c2}{}^4+(\alpha\beta)^2\right]\left|C_H^h\right|^2\right.$$

$$+(\omega\epsilon_2)^2\gamma_2^2\left|B_H^e\right|^2+j\omega\epsilon_2\alpha\beta$$

$$\left.\gamma_2\left[B_H^e\overset{*}{C}{}_H^h-\overset{*}{B}{}_H^e C_H^h\right]\right)d\alpha+\frac{R_s}{2P_{avg}}\frac{1}{2\pi}\int_{\substack{\text{TRIG.}\\ \text{REG.}}}\left(\left[k_{c2}^4\right.\right.$$

$$+ (\alpha\beta)^2 \left| C_T^h \right|^2 + (\omega\epsilon_2)^2 \gamma_2''^2 \left| B_T^e \right|^2$$

$$- \omega\epsilon_2\alpha\beta\gamma_2'' \left[B_T^e \overset{*}{C}{}_H^h - \overset{*}{B}{}_T^e C_H^h \right] \Big) d\alpha . \tag{23}$$

For dielectric attenuation constant,

$$-\frac{dP}{dz} = \frac{1}{2} \iint_{\substack{\text{dielectric} \\ \text{region}}} \bar{J}.\bar{E}^* \, da \tag{24}$$

where

$$J = \sigma \bar{E} . \tag{25}$$

Substituting equation (25) into equation (24) one may obtain,

$$-\frac{dP}{dz} = \frac{1}{2} \int_{-\infty}^{+\infty} \int_0^D \left| \bar{E} \right|^2 dx \, dy$$

$$= \frac{1}{2} \int_{-\infty}^{+\infty} \int_0^D \sigma\left(\left| \bar{E}_x \right|^2 + \left| \bar{E}_y \right|^2 + \left| \bar{E}_z \right|^2 \right) dx \, dy. \tag{26}$$

Substituting field expression into equation (26), applying Parseval's theorem and then substituting transformed scalar potential functions into the resulting equation (A-25), equation (A-34) is obtained.

The y dependence of equation (A-34) disappears through corresponding integrations with respect to y as indicated in equation (A-35 through equation (A-38). The final form of the expression for α_d is obtained as

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \iint_{\substack{HYP.\\REG.}} \Big((\text{Sinh } 2\gamma_2 D - 2\gamma_2 D)$$

$$\Big[(\beta^2\alpha^2 + k_{c2}^4) \, |B_H^e|^2 \frac{1}{4\gamma_2} + (\omega\mu_2)^2 \, |C_H^h|^2 \frac{\gamma_2}{4}$$

$$- \frac{1}{2} \omega\mu_2 \beta\alpha \, \text{Im.}(B_H^e \, \overset{*}{C}{}_H^h) \Big] + (\text{Sinh } 2\gamma_2 D + 2\gamma_2 D)$$

$$\Big[(\omega\mu_2\alpha)^2 \, |C_H^h|^2 \frac{1}{4\gamma_2} + \beta^2 \, |B_H^e|^2 \frac{\gamma_2}{4}$$

$$+ \frac{1}{2} \omega\mu_2 \alpha\beta \, \text{Im.}(\overset{*}{B}{}_H^e \, C_H^h) \Big] \Big) \, d\alpha$$

$$+ \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg}} \frac{1}{2\pi} \iint_{\substack{TRIG.\\REG.}} \Big((2\gamma_2'' D - \text{Sin } 2\gamma_2'' D)$$

$$\Big[(\beta^2\alpha^2 + k_{c2}^4) \, |B_T^e|^2 \frac{1}{4\gamma_2''} + (\omega\mu_2)^2 \, |C_T^h|^2 \frac{\gamma_2''}{4}$$

$$+ \frac{1}{2} \omega\mu_2 \beta\alpha \, \text{Im.}(\, j \, B_T^e \, \overset{*}{C}{}_T^h \,) \Big] + (2\gamma_2'' D$$

$$+ \text{Sin } 2\gamma_2'' D) \Big[(\omega\mu_2\alpha)^2 |C_T^h|^2 \frac{1}{4\gamma_2''}$$

$$+ \beta^2 \, |B_T^e|^2 \frac{\gamma_2''}{4} + \frac{1}{2} \omega\mu_2 \beta\alpha \, \text{Im.}(-j\overset{*}{B}{}_T^e \, C_T^h) \Big] \Big) \, d\alpha \, . \tag{27}$$

Substituting constants derived in [Ref. 6], into equations (22), (23) and (27), the losses may be evaluated numerically.

III. COMPUTATIONAL APPROACH

The computer program developed in [Ref. 6], has been modified and extended to calculate the loss of the microstrip. This program first calculates the phase velocity or λ/λ' ratio for a given geometry of the microstrip and parameters of the substrate. Then the program proceeds and calculates average power flow for the same set of data using results found in the first phase of the calculation, namely λ/λ'. In the final phase, it computes the center conductor loss, dielectric loss and ground plans loss separately.

The program consist of one main and nine subroutines. The main routine starts by calculating all constants and parameters which are needed to evaluate several integrals. First equation (5) is integrated and evaluated for an initial value of λ/λ'. This process continues for different values of λ/λ', until zero is obtained as a result of integration. This time consuming process is shortened by using a root finding routine that determines the correct region of λ/λ' and eliminates the others. Using this routine, an accuracy of 0.01% has been obtained.

Evaluation of the integral is done by standard IBM 360/67 system library subroutine DQG24 which uses 24 point Gaussian quadrature formula and integrates polynomials up to 47^{th} degree.

The DQG24 routine requires an external function subprogram which defines the polynomial to be integrated. For average power calculation, two different subprograms, GZR and GZIM, were used to provide the polynomials for real and imaginary character of γ_2 respectively. For the same purpose, TORA and SULU for the ground plane, GEM and SAY for dielectric, TUL and SIR for conductor losses were used.

The transformed current distribution "(see Chapter IV, equations (28) and (29) " is provided by IBM 360/67 system library subroutine BES which finds the roots of first and second kind of Bessel functions.

The program starts calculating values for the initial frequency and repeats the procedure by increasing the frequency in 1GHz. steps. The number of steps is limited to 50 steps. The program also compares the dielectric half wavelength with the thickness of the substrate, D.

For

$$D = \frac{\lambda}{2\sqrt{\epsilon_r}}$$

the program stops due to the presence of higher order modes.

Because of unavailability of an appropriate convolution subprogram in the IBM 360/67 system library, the limits of the integral equation (A-42) have been extended from $-\infty$ to $+\infty$ to apply Parseval's theorem directly. This approach can not yield an extensive error in the result. Since, most of the field is confined in the dielectric region between the limits -w/2 and w/2. Any error should be small for high permittivity and large values of W/D.

IV. RESULTS AND CONCLUSION

In this study, the current distribution in the z direction (see figure 8),

$$J_z(x) = \begin{cases} \dfrac{1}{\sqrt{x^2 - (\frac{w}{2})^2}} & -w/2 \leqslant x \leqslant w/2 \\ 0 & \text{elsewhere} \end{cases} \tag{28}$$

has been assumed same as by Pucel [Ref. 4]. For an infinitesimely thin strip conductor, the current density diverges at the strip edges at such a rate that the conductor loss is unbounded.

The transform of equation (28),

$$J_z(\alpha) = \pi J_o\left(\frac{\alpha w}{2}\right) \tag{29}$$

is a first kind, zero order Bessel function.

The total conductor loss for rutile (ϵ_r = 105) substrate and for different w/D ratios have been calculated and plotted in figure (1-4) along with Pucel's computational results and measurements for frequencies up to 5GHz. Using the current distribution described above, the two methods give essentially identical results as shown in figure (1-3). In one case, shown in figure (4), a somewhat better agreement to the measurements has been reached. In figure (5-7), results were compared for an alimuna (ϵ_r=9.35) substrate. In figure (5) and

figure (6) a good agreement with the measurements has again been obtained. Figure (7) shows theoretical conductor loss for a microstrip on alimuna. Both Pucel's result and the spectral domain calculation show a large departure from experimental results. According to Pucel /Ref. 4/, this discrepancy might be caused by surface modes or higher order microstrip modes. Since, TM_0 surface mode has a zero cutoff frequency and transverse electric field distribution similar to that for the dominant microstrip mode. Therefore, it might have been propagated with a wide strip. One other possible explanation is that the loss tangent between 1 and 6 GHz. might have been considerably higher than the value measured at 10 GHz. One would expect a higher loss tangent to affect most that case which had the lowest conductor loss, namely figure (7).

Dielectric losses, as calculated using the spectral domain approach and Pucel's approach have been presented in Table 1, II, and III for different substrates and w/D ratios. Results, obtained using the spectral domain technique were slightly higher than Pucel's results. In each case the frequency dependent spectral domain calculation shows a dielectric loss which is relatively large with increasing frequency. This is a reasonable outcome since this analysis accounts for the relatively higher proportion of power which flows in the dielectric region as frequency increases whereas Pucel's quasi-static analysis does not account for this effect.

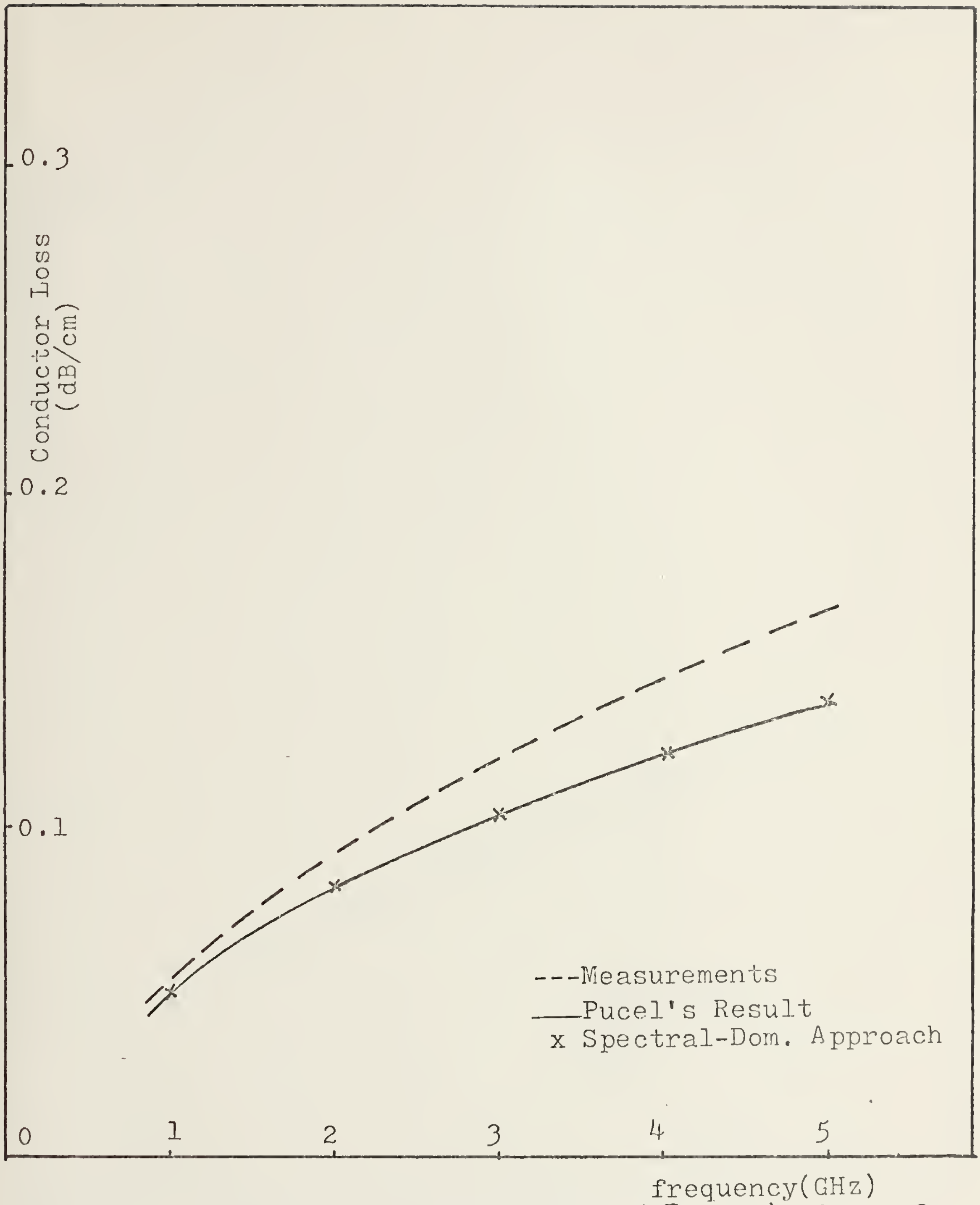

Figure 1. Conductor Loss for rutile (ϵ_r=105), D = .02 and w = .02

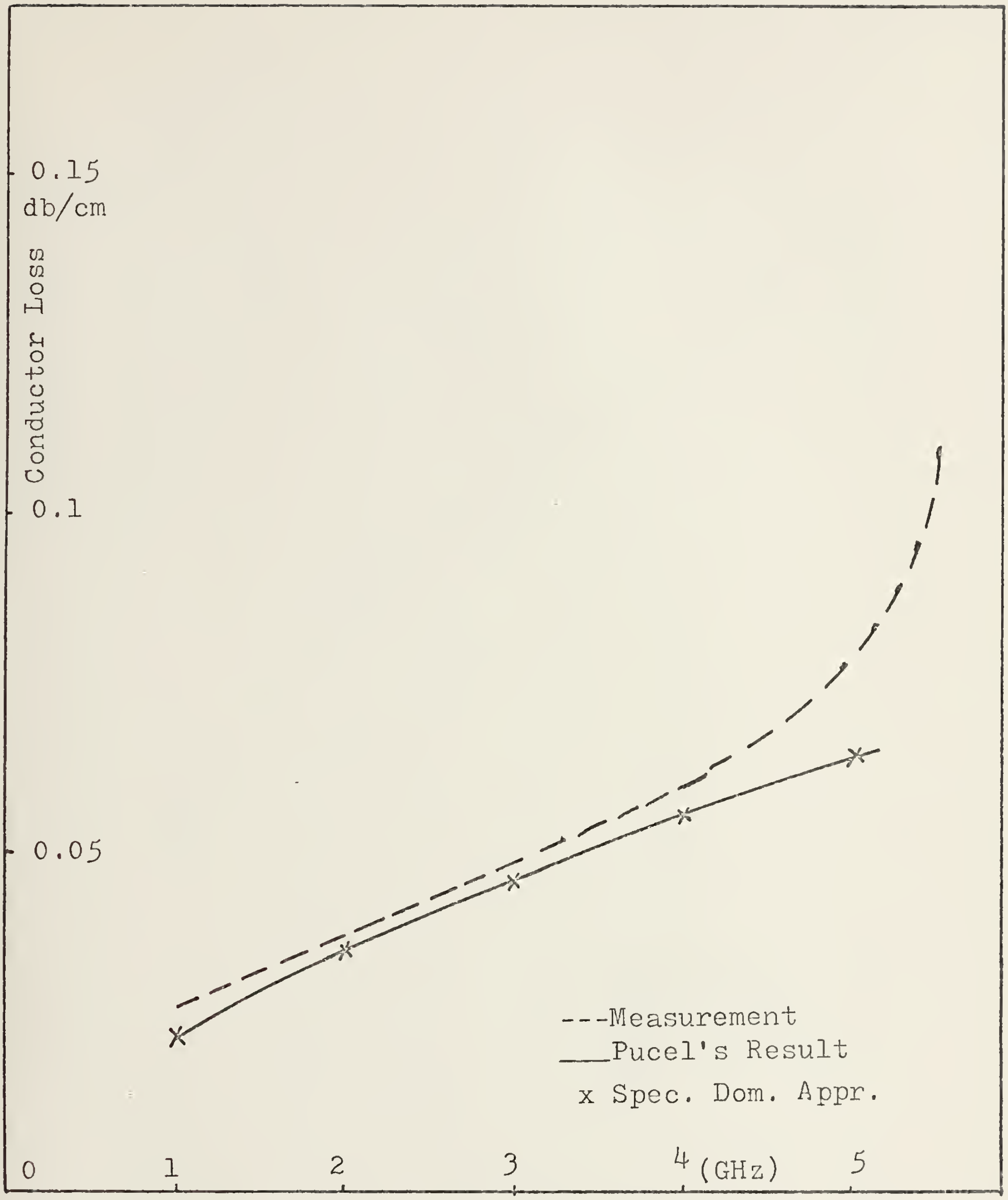

Figure 2. Conductor Loss for rutile ($\epsilon_r = 105$), D = .05 and w = .053

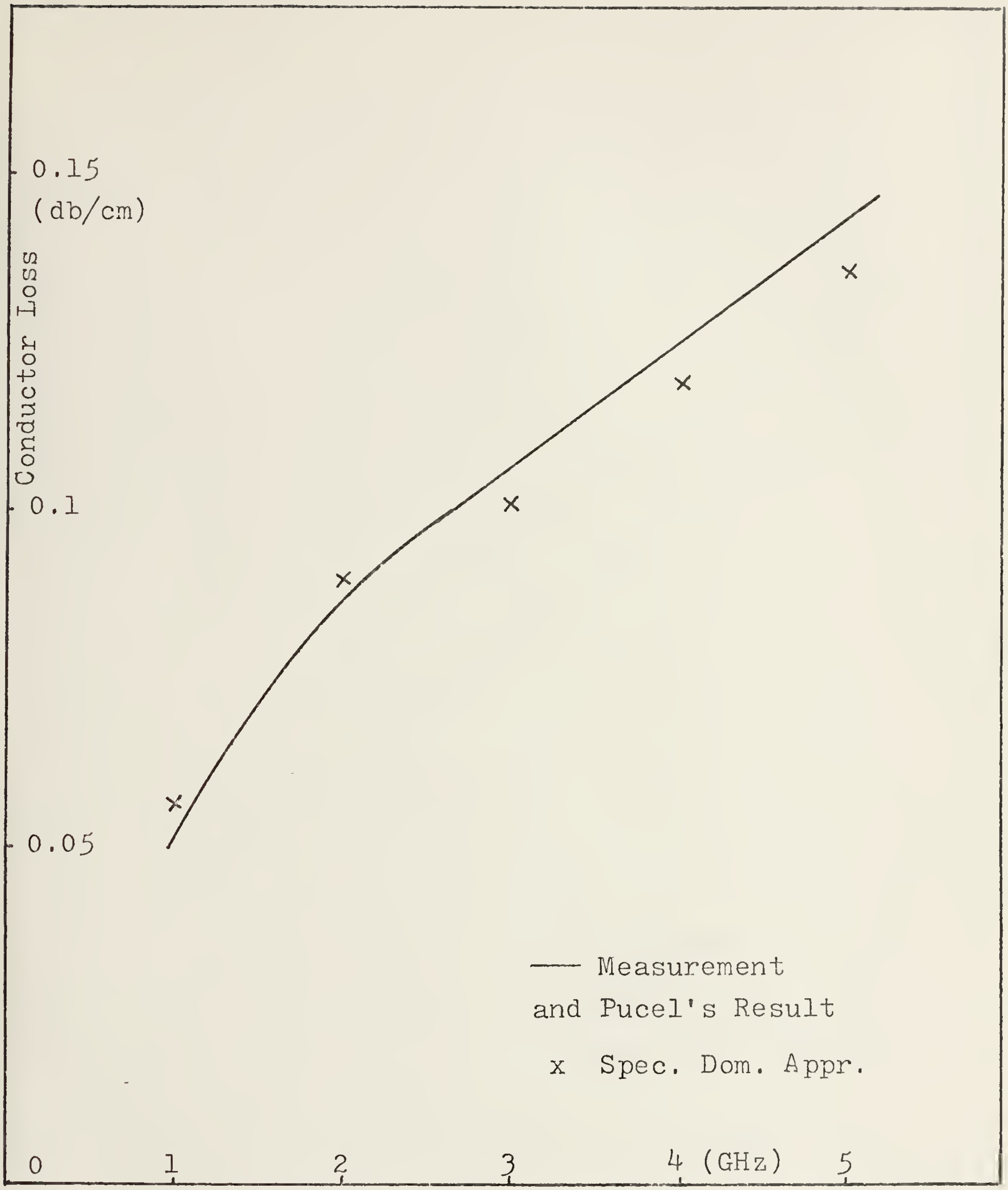

Figure 3. Conductor Loss for rutile ($\epsilon_r = 105$), D = .05 and w = .01

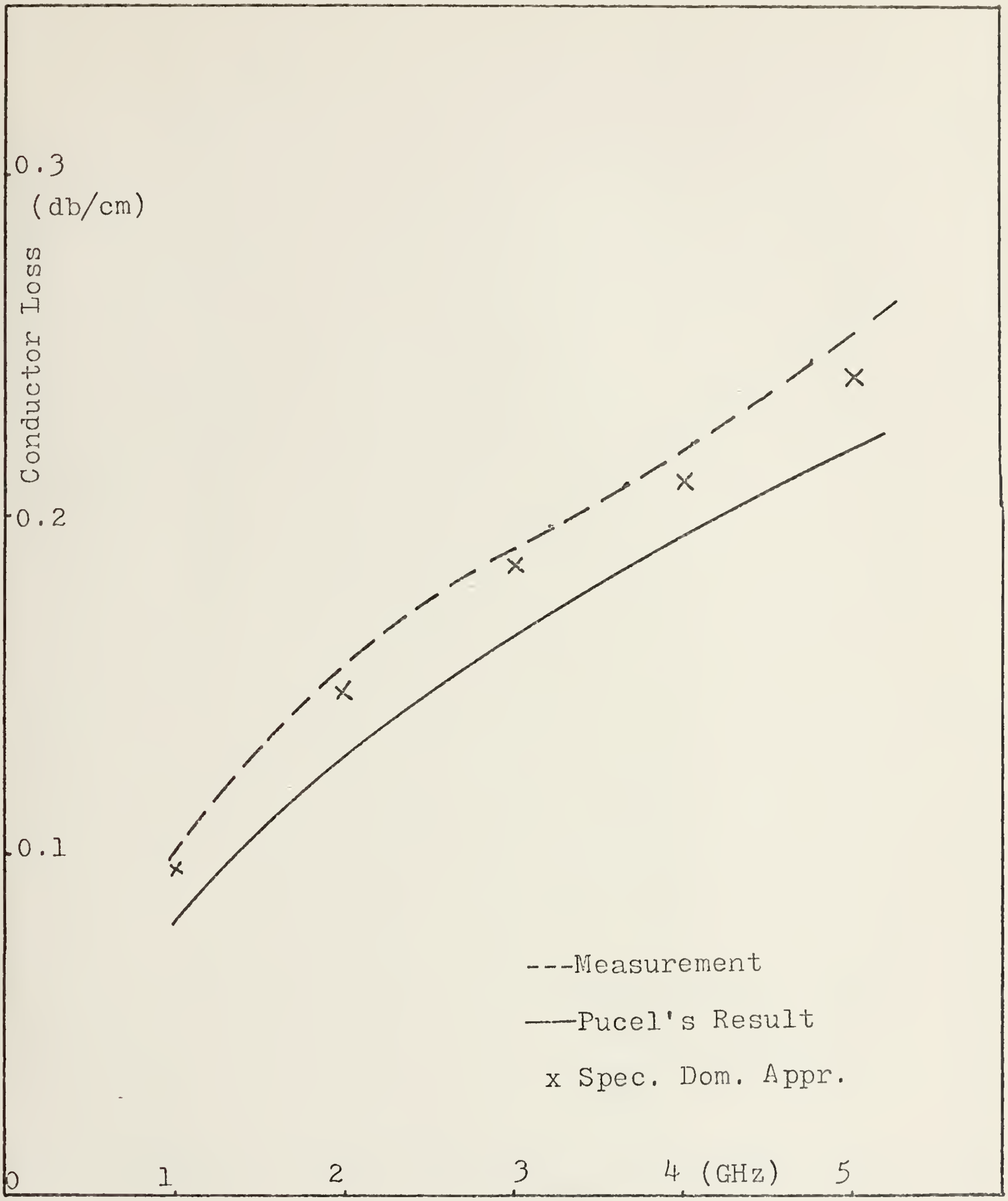

Figure 4. Conductor Loss for rutile ($\epsilon_r = 105$), D = .02 and w = .004

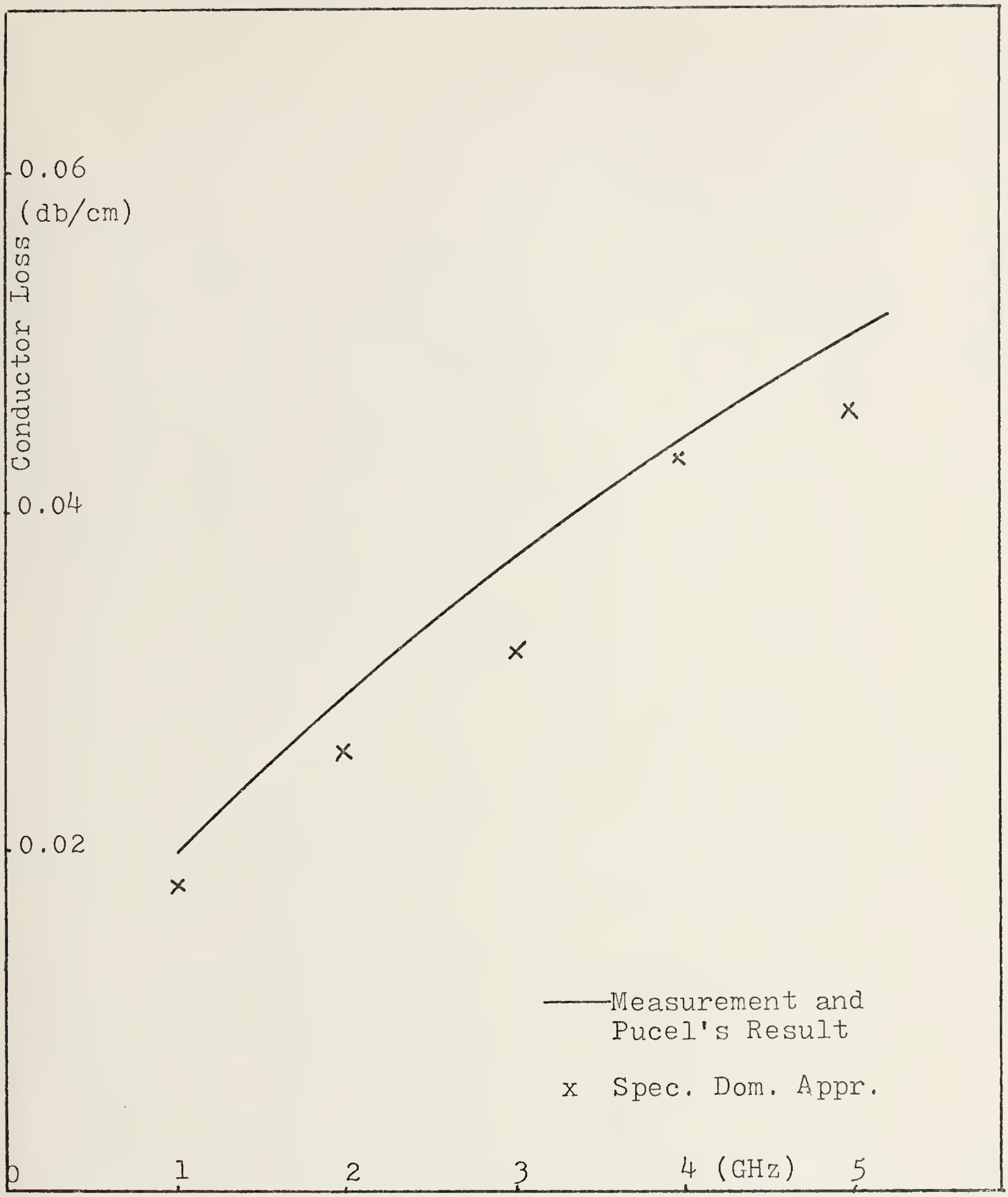

Figure 5. Conductor Loss for Alimuna ($\epsilon_r = 9.35$), D = .02
w = .01

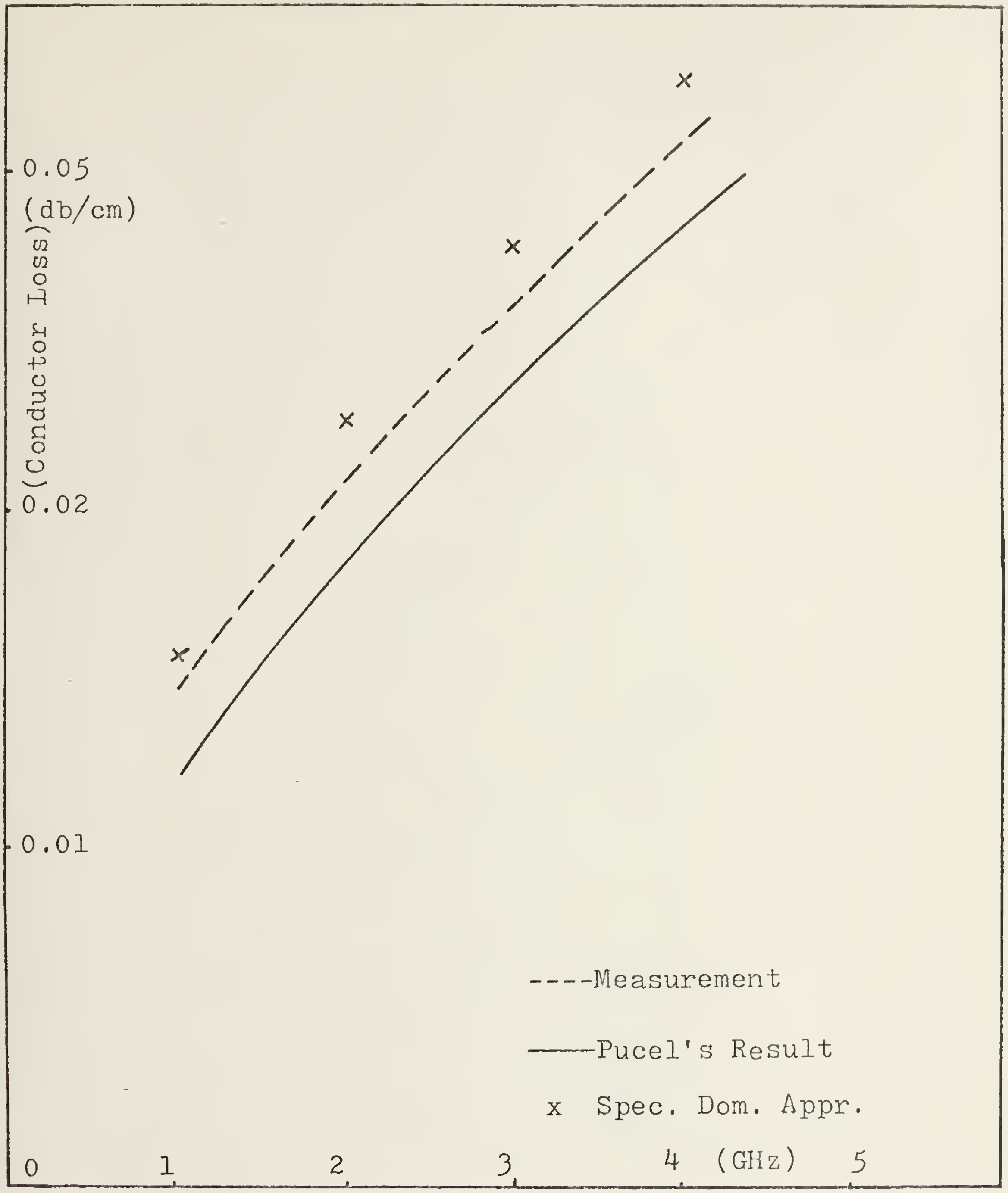

Figure 6. Conductor Loss for Alimuna ($\epsilon_r = 9.35$), D = .02 w = .049

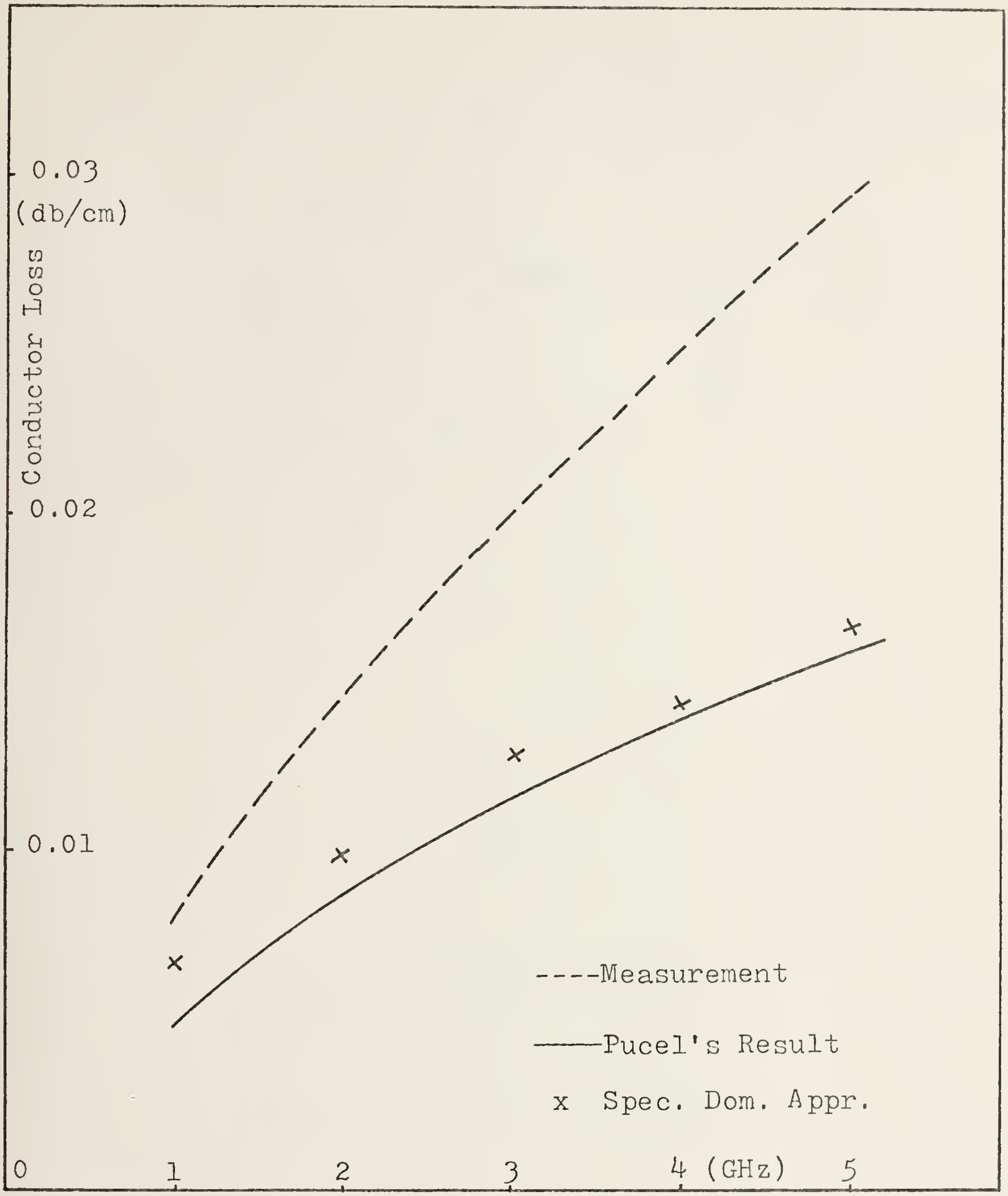

Figure 7. Conductor Loss for Alimuna ($\epsilon_r = 9.35$), D = .05 and w = .12

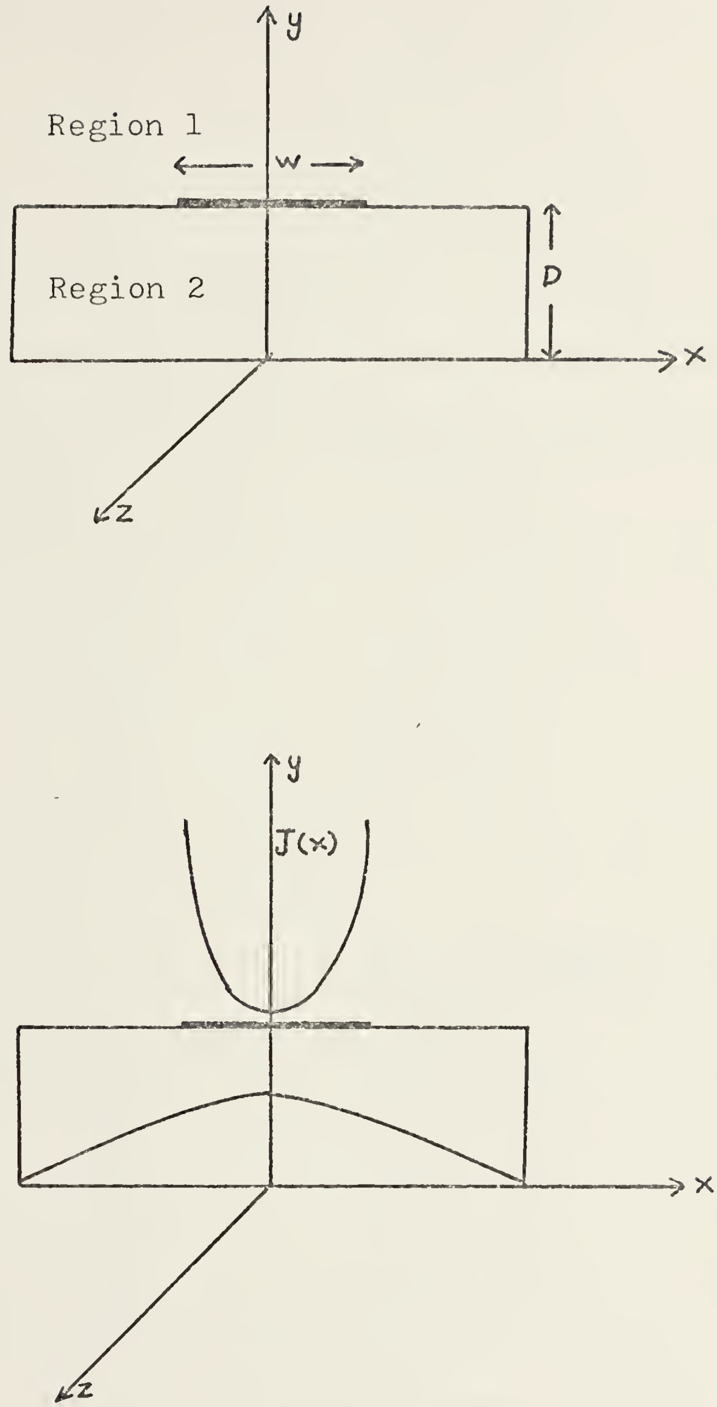

Figure 8. Single strip parameters and the current distributions on the strip and ground plane.

frequency	filling factor	spectral domain d(db/cm)	Pucel's d(db/cm)
1 GHz	.612	7.785×10^{-4}	7.272×10^{-4}
2 GHz	.612	1.648×10^{-3}	1.4545×10^{-3}
3 GHz	.612	2.5935×10^{-3}	2.19×10^{-3}
4 GHz	.612	3.5885×10^{-3}	2.91×10^{-3}
5 GHz	.612	4.61×10^{-3}	3.63×10^{-3}

Table I. Dielectric Losses for rutile substrate and w/D = 1.1

frequency	filling factor	spectral domain d(db/cm)	Pucel's d(db/cm)
1 GHz	.6124	7.51×10^{-4}	7.273×10^{-4}
2 GHz	.6124	1.54×10^{-3}	1.455×10^{-3}
3 GHz	.6124	2.3525×10^{-3}	2.182×10^{-3}
4 GHz	.6124	3.2×10^{-3}	2.91×10^{-3}
5 GHz	.6124	4.1×10^{-3}	3.64×10^{-3}

Table II. Dielectric Losses for rutile substrate and w/D = 1

frequency	filling factor	spectral domain d(db/cm)	Pucel's d(db/cm)
1 GHz	.587	2.08×10^{-4}	2.05×10^{-4}
2 GHz	.587	4.17×10^{-4}	4.11×10^{-4}
3 GHz	.587	6.28×10^{-4}	6.17×10^{-4}
4 GHz	.587	8.4×10^{-4}	8.226×10^{-4}
5 GHz	.587	1.05×10^{-3}	1.027×10^{-3}

Table III. Dielectric Losses for alimuna substrate and w/D = 0.5

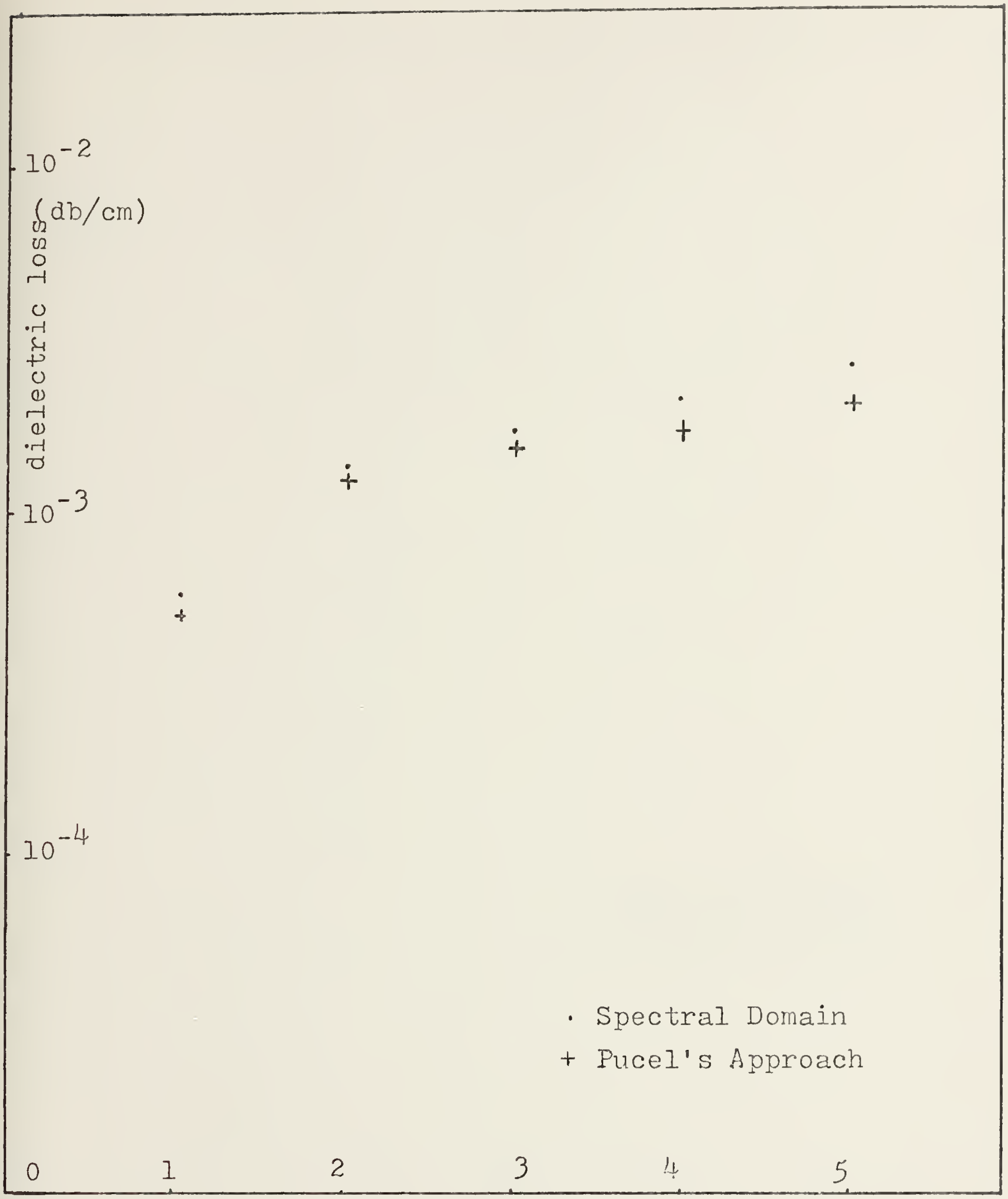

Figure 9. Dielectric Loss for rutile ($\epsilon_r = 105$) substrate and w/D = 1.1

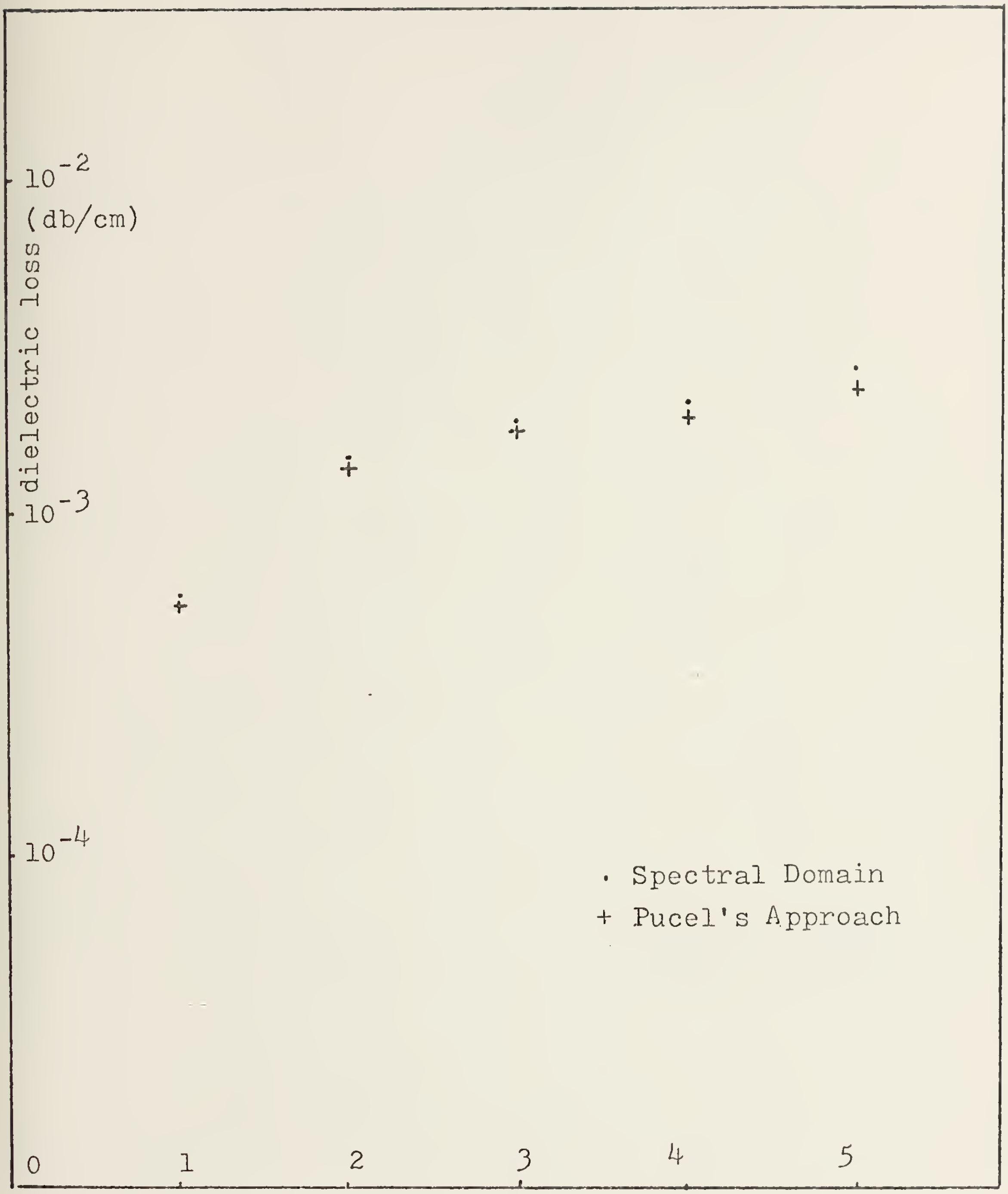

Figure 10. Dielectric Loss for Rutile substrate and w/D = 1

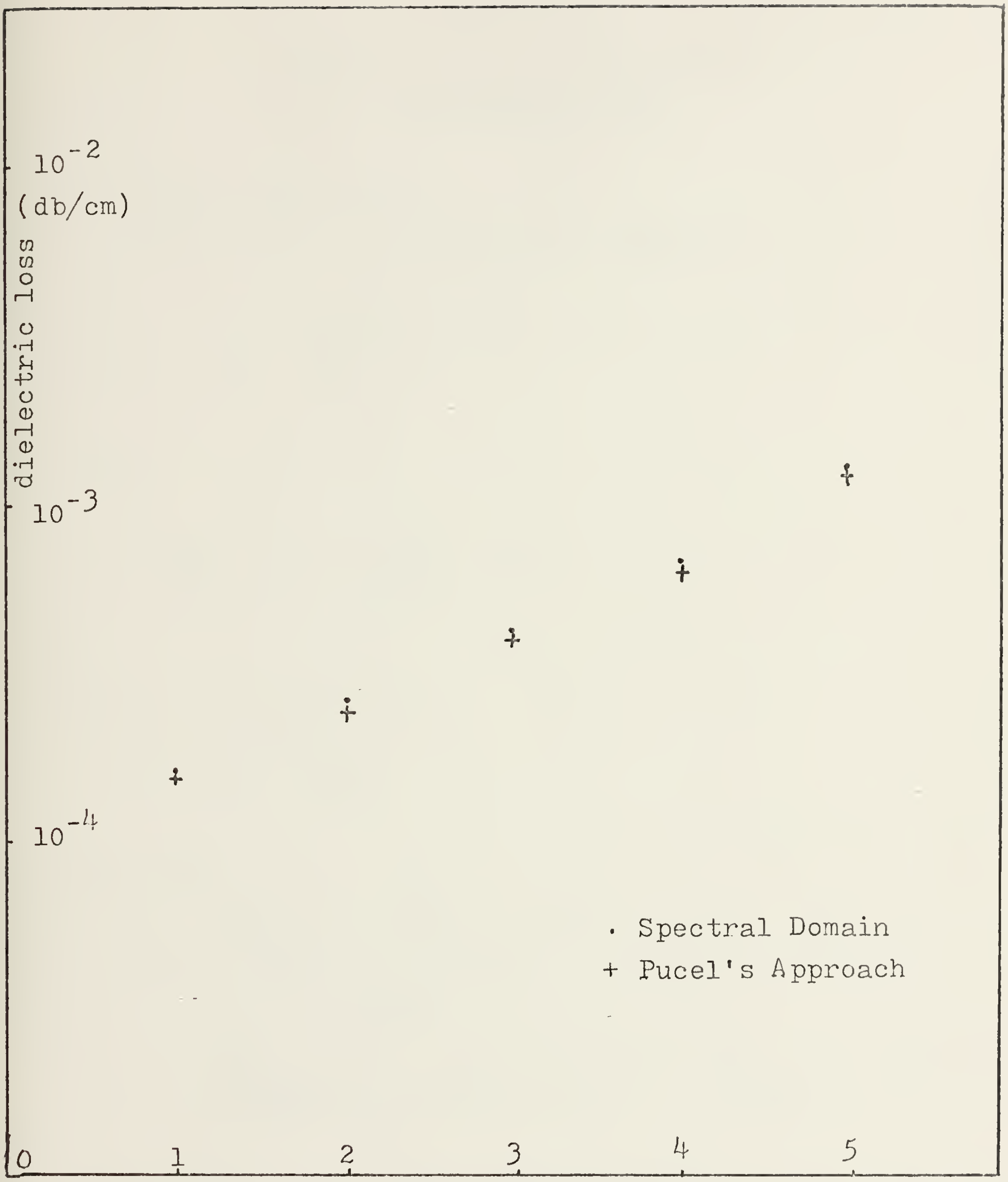

Figure 11. Dielectric Loss for alimuna ($\epsilon_r = 9.35$) substrate and w/D = 0.5

APPENDIX A

SPECTRAL DOMAIN EQUATIONS FOR MICROSTRIP LOSS

A. GROUND PLANE LOSS

Attenuation constant can be express as

$$-\alpha = \frac{1}{2} \quad \frac{dP/dz}{p} \tag{A-1}$$

where

$$-\frac{dP}{dz} = \frac{1}{2} R_s \oint_c |J_s|^2 \cdot dL \ . \tag{A-2}$$

Using the relationship,

$$J_s = \overline{n} \times \overline{H}_{tan.}$$

we obtain

$$\alpha_g = \frac{R_s}{2 P_{avg.}} \int_{-\infty}^{+\infty} |H_{tan.}|^2 \ dx \tag{A-4}$$

$$= \frac{R_s}{2 P_{avg.}} \int_{-\infty}^{+\infty} \left(|H_{x2}(x,o,z)|^2 + |H_{z2}(x,o,z)|^2 \right) dx.$$

Substituting field expressions derived in [Ref. 6] into equation (A-4),

$$\alpha_g = \frac{R_s}{2 P_{avg.}} \int_{-\infty}^{+\infty} \Big[(K_{c2}^2 \, \phi_2^h) \, (k_{c2}^2 \, \phi_2^h) + (J\beta \frac{\partial \phi_2^h}{\partial x} \quad +$$

$$J\omega\epsilon_r \frac{\partial \phi_2^e}{\partial y}\Big) \Big(- J\beta \frac{\partial \phi_2^h}{\partial x} - J\omega\epsilon_2 \frac{\partial \phi_2^e}{\partial y} \Big)\Big]_{y=0} dx \qquad \text{(A-5)}$$

Now apply Parseval's theorem;

$$\alpha_g = \frac{R_s}{2\, P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Big(k_{c2}^4 \left|\Phi_2^h\right|^2 + \Big[J\beta \left(-J\alpha\, \Phi_2^h\right)$$

$$+ J\omega\epsilon_2 \frac{\partial \Phi_2^e}{\partial y} \Big] \cdot \Big[- J\beta \left(-J\alpha\, 0_2^h \right)^* - J\omega\epsilon_2 \frac{\partial \overset{*}{\Phi}{}_2^e}{\partial y} \Big] \Big)_{y=0} d\alpha$$

$$\text{(A-6)}$$

$$\alpha_g = \frac{R_s}{2\, P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Big(\Big[k_{c2}^4 \left|\Phi_2^h\right|^2 \Big] + \Big[\beta\alpha \Phi_2^h + J\omega\epsilon_2 \frac{\partial \Phi_2^e}{\partial y} \Big] \cdot$$

$$\Big[\beta\alpha \overset{*}{\Phi}{}_2^h - J\omega\epsilon_2 \frac{\partial \overset{*}{\Phi}{}_2^e}{\partial y} \Big] \Big)_{y=0} d\alpha \,. \qquad \text{(A-7)}$$

As concluded in [Ref. 6], in the dielectric region, γ_2 may be either real or imaginary depending upon the value of the transform variable α. Transformed scalar potential functions can be described at y=0, as

For $(\gamma_2 D)^2 > 0$, γ_2 is real

$$\frac{\partial \Phi_{2H}^e}{\partial y} (\alpha, 0) = \gamma_2 B_H^e (\alpha) \qquad \text{(A-8)}$$

$$\Phi_{2H}^h (\alpha, 0) = C_H^h (\alpha) \qquad \text{(A-9)}$$

and for $(\gamma_2 D)^2 < 0$, γ_2 is imaginary

$$\frac{\partial \Phi^e_{2T}}{\partial y}(\alpha,\ 0) = j\gamma''_2\ B^e_T(\alpha) \tag{A-10}$$

$$\Phi^h_{2T}(\alpha,\ 0) = C^h_T(\alpha) \tag{A-11}$$

where

$$\gamma_2 = j\gamma''_2\ . \tag{A-12}$$

Substituted equations (A-8) through (A-12) into equation (A-7)

$$g = \frac{R_s}{2\ P_{avg.}}\ \frac{1}{2\pi} \int_{\substack{\text{HYP.}\\ \text{REG.}}} \Bigg(\left[k^4_{c2} + (\alpha\beta)^2\right] \left|C^h_H\right|^2$$

$$+(\omega\epsilon_2)^2\ \gamma_2^2\ \left|B^e_H\right|^2 + \omega\epsilon_2\alpha\beta\ \left[J\gamma_2 B^e_H \overset{*}{C}{}^h_H - J\gamma_2 \overset{*}{B}{}^e_H\ C^h_H\right]\Bigg)\ d\alpha$$

$$+\ \frac{R_s}{2\ P_{avg.}}\ \frac{1}{2\pi} \int_{\substack{\text{TRIG}\\ \text{REG.}}} \Bigg(\left[k^4_{c2} + (\alpha\beta)^2\right] \left|C^h_T\right|^2$$

$$+(\omega\epsilon_2)^2 \gamma''^2_2\ \left|B^e_T\right|^2 + \omega\epsilon_2\alpha\beta\ \left[-\gamma''_2 B^e_T\ \overset{*}{C}{}^h_T + \gamma''_2 \overset{*}{B}{}^e_T\ C^h_T\right|\Bigg)\ d\alpha$$

(A-13)

B. DIELECTRIC LOSS

Dielectric attenuation constant can be described as

$$\alpha_d = -\frac{1}{2}\ \frac{(dp/dz)_{\text{dielectric}}}{P_{\text{avg.}}} = \frac{1}{2\ P_{\text{avg.}}} \iint_{\substack{\text{Region} \\ 2}} \bar{J}\cdot\bar{E}^{*}\ da$$

or

$$\alpha_d = \frac{1}{2\ P_{\text{avg.}}} \int_{-\infty}^{+\infty}\int_{0}^{D} \sigma\,|E|^2\ dxdy. \tag{A-14}$$

Using the relationship for conductivity,

$$\sigma = \omega\epsilon'' = \omega\epsilon'\tan\delta \tag{A-15}$$

we obtain

$$\alpha_d = \frac{\omega\epsilon'\tan\delta}{2\ P_{\text{avg.}}} \int_{-\infty}^{+\infty}\int_{0}^{D} |E_x|^2 + |E_y|^2 + |E_z|^2\ )\ dx\ dy$$

or

$$\alpha_d = \frac{2\pi}{\lambda}\ \frac{\epsilon_r \tan\delta}{2\,\eta_o\,P_{\text{avg.}}} \int_{-\infty}^{+\infty}\int_{0}^{D} (\ |E_x|^2 + |E_y|^2 + |E_z|^2\ )\ dxdy. \tag{A-16}$$

Using field expressions derived in [Ref. 6]

$$|E_x|^2 = \left(j\beta \frac{\partial \phi^e}{\partial x} - j\omega\mu \frac{\partial \phi^h}{\partial y} \right) \left(-j\beta \frac{\partial \phi^e}{\partial x} + j\omega\mu \frac{\partial \phi^h}{\partial y} \right) \qquad \text{(A-17)}$$

$$|E_y|^2 = \left(j\beta \frac{\partial \phi^e}{\partial y} + j\omega\mu \frac{\partial \phi^h}{\partial x} \right) \left(-j\beta \frac{\partial \phi^e}{\partial y} - j\omega\mu \frac{\partial \phi^h}{\partial x} \right) \qquad \text{(A-18)}$$

$$|E_z|^2 = (k_c^2 \; \phi^e)(k_c^2 \; \phi^e) \qquad \text{(A-19)}$$

and substituting these equations into dielectric loss equation (A-16),

$$\alpha_d = \frac{2\pi}{\lambda} \; \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg}} \int_{-\infty}^{+\infty}\int_{0}^{D} \Big[\left(J\beta \frac{\partial \phi^e}{\partial x} - J\omega\mu \frac{\partial \phi^h}{\partial y} \right) \left(-J\beta \frac{\partial \phi^e}{\partial x} + J\omega\mu \frac{\partial \phi^h}{\partial y} \right) + \left(J\beta \frac{\partial \phi^e}{\partial y} + J\omega\mu \frac{\partial \phi^h}{\partial x} \right) \left(-J\beta \frac{\partial \phi^e}{\partial y} - J\omega\mu \frac{\partial \phi^h}{\partial x} \right) + (k_c^2 \; \phi^e)(k_c^2 \; \phi^e) \Big] \, dx \, dy. \qquad \text{(A-20)}$$

Now, apply Parseval's theorem: $\phi^e(x,y)$, $\phi^h(x,y)$ real then

$$\int_{-\infty}^{+\infty}\int_{0}^{D} f_1(x,y) \, f_2(x,y) \, dxdy = \frac{1}{2\pi} \int_{-\infty}^{+\infty}\int_{0}^{D} F_1(\alpha, y) F_2^*(\alpha, y) \, d\alpha dy$$

thus,

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty}\int_0^D \Bigg(\left[J\beta\,(-J\alpha\ \Phi^e) - J\omega\mu \frac{\partial \Phi^h}{\partial y}\right]$$

$$\cdot \left[-J\beta\,(-J\alpha\ \Phi^e)^* + J\omega\mu \frac{\partial \overset{*}{\Phi}{}^h}{\partial y}\right] + \left[J\beta \frac{\partial \Phi^e}{\partial y} + J\omega\mu\,(-J\alpha\ \Phi^h)\right]$$

$$\cdot \left[-J\beta \frac{\partial \overset{*}{\Phi}{}^e}{\partial y} - J\omega\mu\,(-J\alpha\ \Phi^h)^*\right] + \left[k_c^2\ \Phi^e\right]\left[k_c^2\ \Phi^e\right]\Bigg) d\alpha\, dy$$

(A-21)

It then follows that

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty}\int_0^D \Bigg(\left[\alpha\beta\Phi^e - J\omega\mu \frac{\partial \Phi^h}{\partial y}\right]\Bigg[\alpha\beta\overset{*}{\Phi}{}^e$$

$$+ J\omega\mu \frac{\partial \overset{*}{\Phi}{}^h}{\partial y}\Bigg] + \left[J\beta \frac{\partial \Phi^e}{\partial y} + \omega\mu\alpha\Phi^h\right]\left[-J\beta \frac{\partial \overset{*}{\Phi}{}^e}{\partial y} + \omega\mu\alpha\overset{*}{\Phi}{}^h\right]$$

$$+ \left[K_c^4\ \Phi^e\ \overset{*}{\Phi}{}^e\right]\Bigg) d\alpha dy, \qquad \text{(A-22)}$$

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty}\int_0^D \Bigg(\Bigg[(\beta\alpha)^2 \left|\Phi_2^e\right|^2 + (\omega\mu)^2 \left|\frac{\partial \Phi_2^h}{\partial y}\right|^2$$

$$+ J\omega\mu\beta\alpha \left(\Phi_2^e \frac{\partial \overset{*}{\Phi}{}_2^h}{\partial y} - \overset{*}{\Phi}{}_2^e \frac{\partial \Phi_2^h}{\partial y} \right)\Bigg] + \Bigg[\beta^2 \left| \frac{\partial \Phi_2^e}{\partial y}\right|^2$$

$$+ (\omega\mu\alpha)^2 \left|\Phi_2^h\right|^2 + J\omega\mu\beta\alpha \left(\overset{*}{\Phi}{}_2^h \frac{\partial \Phi_2^e}{\partial y} - \Phi_2^h \frac{\partial \overset{*}{\Phi}{}_2^e}{\partial y} \right)$$

$$+ k_{c2}^4 \left|\Phi_2^e\right|^2 \Bigg) d\alpha\ dy\ , \qquad \text{(A-23)}$$

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty}\int_{0}^{D} \Bigg(\left[(\beta\alpha)^2 + k_{c2}^4 \right] \left| \Phi_2^e \right|^2$$

$$+ (\omega\mu\alpha)^2 \left| \Phi_2^h \right|^2 + (\omega\mu)^2 \left| \frac{\partial \Phi_2^h}{\partial y} \right|^2 + \beta^2 \left| \frac{\partial \Phi_2^e}{\partial y} \right|^2$$

$$+ J\omega\mu\beta\alpha(2J) \quad \mathrm{Im.} \left[\Phi_2^e \frac{\partial \Phi_2^{*h}}{\partial y} - \Phi_2^h \frac{\partial \Phi_2^{*e}}{\partial y} \right] \Bigg) \, d\alpha \, dy,$$

$$\text{(A-24)}$$

and

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{-\infty}^{+\infty}\int_{0}^{D} \Bigg(\left[(\beta\alpha)^2 + k_{c2}^4 \right] \left| \Phi_2^e \right|^2$$

$$+ (\omega\mu\alpha)^2 \left| \Phi_2^h \right|^2 + (\omega\mu)^2 \left| \frac{\partial \Phi_2^h}{\partial y} \right|^2 + \beta^2 \left| \frac{\partial \Phi_2^e}{\partial y} \right| + 2\omega\mu$$

$$\alpha\beta \ \mathrm{Im} \left[\Phi_2^h \frac{\partial \Phi_2^e}{\partial y} - \Phi_2^e \frac{\partial \Phi_2^{*h}}{\partial y} \right] \Bigg) \quad d\alpha \, dy \, . \qquad \text{(A-25)}$$

For $(\gamma_2 D)^2 > 0$, γ_2 is real and

$$\Phi_{2H}^e (\alpha, y) = B_H^e (\alpha) \operatorname{Sinh} \gamma_2 y \qquad \text{(A-26)}$$

$$\frac{\partial \Phi_{2H}^e}{\partial y} (\alpha, y) = \gamma_2 B_H^e (\alpha) \operatorname{Cosh} \gamma_2 y \qquad \text{(A-27)}$$

$$\Phi_{2H}^h (\alpha, y) = C_H^h (\alpha) \operatorname{Cosh} \gamma_2 y \qquad \text{(A-28)}$$

$$\frac{\partial \Phi_{2H}^h}{\partial y} (\alpha, y) = \gamma_2 B_H^h (\alpha) \operatorname{Sinh} \gamma_2 y \, . \qquad \text{(A-29)}$$

For $(\gamma_2 D)^2 > 0$, γ_2 is imaginary and

$$\Phi^e_{2T}(\alpha, y) = j\, B^e_T(\alpha)\ \mathrm{Sin}\ \gamma''_2 y \tag{A-30}$$

$$\frac{\partial \Phi^e_{2T}}{\partial y}(\alpha, y) = j\,\gamma''_2\ B^e_T(\alpha)\ \mathrm{Cos}\ \gamma''_2 y \tag{A-31}$$

$$\Phi^h_{2T}(\alpha, y) = C^h_T(\alpha)\ \mathrm{Cos}\ \gamma''_2 y \tag{A-32}$$

$$\frac{\partial \Phi^h_{2T}}{\partial y}(\alpha, y) = -\gamma''_2\ C^h_T(\alpha)\ \mathrm{Sin}\ \gamma''_2 y \tag{A-33}$$

where

$$\gamma_2 = j\gamma''_2 \ .$$

Substituting equations (A-26) through (A-33), into equation (A-25),

$$\alpha_d = \frac{2\pi}{\lambda}\ \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}}\ \frac{1}{2\pi} \int_{HYP}\int_0^D \Big(\Big[(\beta\alpha)^2 + k^4_{c2}\Big]\Big|B^e_H\Big|^2$$

$$\mathrm{Sinh}^2\gamma_{2y} + \Big|C^h_H\Big|^2 (\omega\mu\alpha)^2\ \mathrm{Cosh}^2\gamma_2 y + (\omega\mu)^2\gamma^2_2$$

$$\mathrm{Sinh}^2\gamma_2 y\ \Big|C^h_H\Big|^2 + \beta^2\Big|B^e_H\Big|^2\gamma^2_2\ \mathrm{Cosh}^2\gamma_2 y$$

$$+\ 2\omega\mu\beta\alpha\,\mathrm{Im.}\Big[(C^h_H\ \mathrm{Cosh}\ \gamma_2 y)(\gamma_2\ B^{*e}_H\ \mathrm{Cosh}\ \gamma_2 y)$$

$$-\ (B^e_H\ \mathrm{Sinh}\ \gamma_2 y)(\gamma_2\ C^{*h}_H\ \mathrm{Sinh}\ \gamma_2 y)\Big]\Big)\ d\alpha\, dy$$

$$+\ \frac{2\pi}{\lambda}\ \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}}\ \frac{1}{2\pi} \int_{\substack{TRIG\\REG.}}\int_0^D \Big(\Big[(\beta\alpha)^2$$

$$+ K_{c2}^4 \Big] \left| B_T^e \right|^2 \sin^2 \gamma''_2 y + (\omega\mu\alpha)^2 \left| C_T^h \right|^2 \cos^2 \gamma''_2 y$$

$$+ 2\omega\mu\alpha\beta \,\mathrm{Im.} \Big[(C_T^h \cos \gamma''_2 y) (-J \gamma''_2 B_T^{*e} \cos \gamma''_2 y)$$

$$- (J B_T^e \sin \gamma''_2 y) (- \gamma''_2 \; C_T^{*h} \sin \gamma''_2 y) \Big] \Big) d\alpha \; dy.$$

Now note that,

$$\int_0^D \sinh^2 \gamma_2 y \; dy = \frac{1}{4\gamma_2} \Big[\sinh 2\gamma_2 D - 2\gamma_2 D \Big] \qquad \text{(A-35)}$$

$$\int_0^D \cosh^2 \gamma_2 y \; dy = \frac{1}{4\gamma_2} \Big[\sinh 2\gamma_2 D + 2\gamma_2 D \Big] \qquad \text{(A-36)}$$

$$\int_0^D \sin^2 \gamma''_2 y \; dy = \frac{1}{4\gamma''_2} \Big[2\gamma''_2 D - \sin 2\gamma''_2 D \Big] \qquad \text{(A-37)}$$

$$\int_0^D \cos^2 \gamma''_2 y \; dy = \frac{1}{4\gamma''_2} \Big[2\gamma''_2 D + \sin 2\gamma''_2 D \Big]. \qquad \text{(A-38)}$$

Substituting equations (A-35) through (A-38) into equation (A-34),

$$\alpha_d = \frac{2\pi}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{\substack{\text{HYP.}\\ \text{REG.}}} \Big(\Big[(\beta\alpha)^2 + k_{c2}^4 \Big] \left| B_H^e \right|^2 \frac{1}{4\gamma_2}$$

$$\Big[\sinh 2\gamma_2 D - 2\gamma_2 D \Big] + (\omega\mu_2\alpha)^2 \left| C_H^h \right|^2 \frac{1}{4\gamma_2} \Big[\sinh 2\gamma_2 D$$

$$+ 2\gamma_2 D\Big] + (\omega\mu_2)^2 \left| C_H^h \right|^2 \frac{\gamma_2}{4} \Big[\text{Sinh } 2\gamma_2 D - 2\gamma_2 D\Big]$$

$$+ \beta^2 \left| B_H^e \right|^2 \frac{\gamma_2}{4} \Big[\text{Sinh } 2\gamma_2 D + 2\gamma_2 D\Big] + 2\omega\mu_2\beta\alpha \text{ Im.}$$

$$\Big[C_H^h \; B_H^{*e}\Big] \frac{1}{4} \Big[\text{Sinh } 2\gamma_2 D + 2\gamma_2 D\Big] - 2\omega\mu\beta\alpha \text{Im.}$$

$$\Big[B_H^e \; C_H^{*h}\Big] \frac{1}{4} \Big[\text{Sinh } 2\gamma_2 D - 2\gamma_2 D\Big]\Big) d\alpha + \frac{2\pi}{\lambda}$$

$$\frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \frac{1}{2\pi} \int_{\substack{\text{TRIG.}\\\text{REG.}}} \Big[(\beta\alpha)^2 + k_{c2}^4\Big] \left| B_T^e \right|^2 \frac{1}{4\gamma_2''}$$

$$\Big[2\gamma_2'' D - \text{Sin } 2\gamma_2'' D\Big] + (\omega\mu\alpha)^2 \left| C_T^h \right|^2 \frac{1}{4\gamma_2''} \Big[2\gamma_2'' D + \text{Sin } 2\gamma_2'' D\Big]$$

$$+(\omega\mu)^2 \left| C_T^h \right|^2 \frac{\gamma_2''}{4} \Big[2\gamma_2'' D - \text{Sin } 2\gamma_2'' D\Big] + \beta^2 \left| B_T^e \right|^2$$

$$\frac{\gamma_2''}{4} \Big[2\gamma_2'' D + \text{Sin } 2\gamma_2'' D\Big] + 2\omega\mu\alpha\beta \text{ Im.} \Big[-JC_T^h \; B_T^{*e}\Big] \frac{1}{4}$$

$$\Big[2\gamma_2'' D + \text{Sin } 2\gamma_2'' D\Big] + 2\omega\mu\beta\alpha \text{ Im.} \Big[J \; B_T^e \; C_T^{*h}\Big] \frac{1}{4}$$

$$\Big[2\gamma_2'' D - \text{Sin } 2\gamma_2'' D\Big]\Big) d\alpha . \qquad \text{(A-39)}$$

Finally, normalizing with D, one obtain

$$\alpha_d = \frac{D}{\lambda} \frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}} \int_{\substack{\text{HYP.}\\\text{REG.}}} \Big(\Big(\Big[(\beta D)^2 (\alpha D)^2 + (k_{c2} D)^4\Big] \left| \frac{B_H^e}{D^2} \right|^2$$

$$\frac{1}{4\gamma_2 D}\left[\text{Sinh } 2\gamma_2 D - 2\gamma_2 D\right] + (\omega\mu_2 D)^2(\alpha D)^2\left|\frac{C_H^h}{D^2}\right|^2$$

$$\frac{1}{4\gamma_2 D}\left[\text{Sinh } 2\gamma_2 D + 2\gamma_2 D\right] + (\omega\mu_2 D)^2\left|\frac{C_H^h}{D^2}\right|^2 \frac{\gamma_2 D}{4}$$

$$\left[\text{Sinh } 2\gamma_2 D - 2\gamma_2 D\right] + (\beta D)^2 \left|\frac{B_H^e}{D^2}\right|^2 \frac{\gamma_2 D}{4}\left[\text{Sinh } 2\gamma_2 D\right.$$

$$\left. + 2\gamma_2 D\right] + 2(\omega\mu_2 D)(\beta D)(\alpha D) \text{ Im. } \left[\frac{C_H^h}{D^2} \quad \frac{B_H^{*e}}{D^2}\right]\frac{1}{4}$$

$$\left[\text{Sinh } 2\gamma_2 D + 2\gamma_2 D\right] - 2(\omega\mu_2 D)(\beta D)(\alpha D) \text{ Im.}$$

$$\left.\left[\frac{B_H^e}{D^2} \quad \frac{C_H^{*h}}{D^2}\right]\frac{1}{4}\left[\text{Sinh } 2\gamma_2 D - 2\gamma_2 D\right]\right) d(\alpha D)$$

$$+ \frac{D}{\lambda}\,\frac{\epsilon_r \tan\delta}{2\eta_o P_{avg.}}\int_{\substack{\text{TRIG.}\\ \text{REG.}}}\left(\left[(\beta D)^2(\alpha D)^2 + (k_{c2}D)^4\right]\left|\frac{B_T^e}{D^2}\right|^2\right.$$

$$\frac{1}{4\gamma_2''}\left[2\gamma_2'' D - \text{Sin } 2\gamma_2'' D\right] + (\omega\mu_2 D)^2(\alpha D)^2\left|\frac{C^h}{D^2}\right|^2$$

$$\frac{1}{4\gamma_2'' D}\left[2\gamma_2'' D + \text{Sin } 2\gamma_2'' D\right] + (\omega\mu_2 D)^2\left|\frac{C^h}{D^2}\right|^2$$

$$\frac{\gamma_2'' D}{4}\left[2\gamma_2'' D - \text{Sin } 2\gamma_2'' D\right] + (\beta D)^2\left|\frac{B^e}{D^2}\right|^2\frac{\gamma_2'' D}{4}$$

$$\left[2\gamma_2'' D + \text{Sin } 2\gamma_2'' D\right] + 2(\omega\mu_2 D)(\beta D)(\alpha D) \text{ Im.}$$

$$\left[-J\,\frac{C^h}{D^2}\,\frac{B^{*e}}{D^2}\right]\frac{1}{4}\left[2\gamma_2'' D + \text{Sin } 2\gamma_2'' D\right] + 2(\omega\mu_2 D)$$

$$(\beta D)(\alpha D) \quad \mathrm{Im}\left[J \quad \frac{B_T^e}{D^2} \quad \frac{C_T^{*h}}{D^2} \right] \frac{1}{4} \left[2\gamma_2'' D \right.$$

$$\left. - \sin 2\gamma_2'' D \right] \Big) \; d(\alpha D) \tag{A-40}$$

C. STRIP CONDUCTOR LOSS

$$\alpha_c = \frac{R_s}{2 P_{avg.}} \oint_c |J_s|^2 \, dl \tag{A-41}$$

and substituting $J_s = \bar{n} \times \bar{H}_{tan.}$ into equation (A-41) ,

$$\alpha_c = \frac{R_s}{2 P_{avg.}} \oint_{cond.} |H_{tan.}|^2 \, dl$$

$$= \frac{R_s}{2 P_{avg.}} \int_{-w/2}^{+w/2} \left(|H_{x1}(x,D)|^2 + |H_{x2}(x,D)|^2 \right) dx. \tag{A-42}$$

$$\text{let } f(x) = \begin{cases} 1 & -w/2 \leqslant x \leqslant w/2 \\ 0 & \text{elsewhere} \end{cases} \tag{A-43}$$

then,

$$\alpha_c(\mathrm{top}) = \frac{R_s}{2P_{avg.}} \int_{-\infty}^{+\infty} f(x)\, H_{x1}(x,D)\, H_{x1}^*(x,D)\, dx. \tag{A-44}$$

Substituting field expressions derived in [Ref. 6] into equation (A-44)

$$\alpha_c(\mathrm{top}) = \frac{R_s}{2 P_{avg.}} \int_{-\infty}^{+\infty} f(x) \left(j\beta \frac{\partial \phi_1^h}{\partial x} + j\omega\epsilon_1 \frac{\partial \phi_1^e}{\partial y} \right)$$

$$(- j\beta \frac{\partial \phi_1^h}{\partial x} - j\omega \epsilon_1 \frac{\partial \phi_1^e}{\partial y}) \; dx \, . \qquad \text{(A-45)}$$

The transform of f(x) is

$$F(\alpha) = \int_{-\infty}^{+\infty} f(x) \; e^{j\alpha x} \, dx = w \left(\frac{\operatorname{Sin} \frac{w\alpha}{2}}{\frac{w\alpha}{2}} \right) . \qquad \text{(A-46)}$$

Now, apply Parseval's theorem to obtain

$$\alpha_c(\text{top}) = \frac{R_s}{2 \; P_{avg.}} \; \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left(\left[j\beta \, (-j\alpha \, \Phi_1^h \,)^* + j\omega\epsilon_1 \frac{\partial \Phi_1^e}{\partial y} \right] \right.$$

$$\cdot \; \frac{1}{2\pi} \int_{-\infty}^{+\infty} w \frac{\operatorname{Sin}(\alpha - \rho)\frac{w}{2}}{(\alpha - \rho)\frac{w}{2}} \left[- j\beta \, (-j\alpha \; \Phi_1^h \,) \right.$$

$$\left. \left. - j\omega\epsilon_1 \; \frac{\partial \Phi_1^e}{\partial y} \right] d\rho \right) \quad d\alpha$$

or

$$\alpha_c(\text{top}) = \frac{R_s}{2 \; P_{avg.}} \left(\frac{1}{2\pi} \right)^2 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \left[\beta\alpha \overset{*}{\Phi}{}_1^h \, (\alpha) + j\omega\epsilon_1 \right.$$

$$\left. \frac{\partial \overset{*}{\Phi}{}_1^e(\alpha)}{\partial y} \right] \cdot \quad w \left[\frac{\operatorname{Sin}(\alpha - \rho) \; \frac{w}{2}}{(\alpha - \rho)\frac{w}{2}} \right]$$

$$\left[-\beta\alpha \Phi_1^h(\rho) - j\omega\epsilon_1 \; \frac{\partial \Phi_1^e(\rho)}{\partial y} \right] \quad d\rho \; d\alpha \, . \qquad \text{(A-47)}$$

From the dispersion calculation, equations 116, 117, 118, 119 in [Ref. 6], at y = D

$$\Phi_1^e(\alpha, D) = A^e(\alpha) \tag{A-48}$$

$$\frac{\partial \Phi_1^e(\alpha, D)}{\partial y} = -\gamma_1 A^e(\alpha) \tag{A-49}$$

$$\Phi_1^h(\alpha, D) = A^h(\alpha) \tag{A-50}$$

$$\frac{\partial \Phi_1^h(\alpha, D)}{\partial y} = -\gamma_1 A^h(\alpha) \tag{A-51}$$

Substituting these results into equation (A-47),

$$\alpha_c(\text{top}) = \frac{R_s}{2\,P_{avg.}}\left(\frac{1}{2\pi}\right)^2 \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left[\beta\alpha A^{*h} - j\omega\epsilon_1\gamma_1 A^{*e}\right] w$$

$$\left[\frac{\mathrm{Sin}(\alpha-\rho)\frac{w}{2}}{(\alpha-\rho)\frac{w}{2}}\right]\left[-\beta\alpha A^h(\rho) + j\omega\epsilon_1\gamma_1 A^e(\rho)\right] d\rho\, d\alpha. \tag{A-52}$$

Putting the equation into normalized form;

$$\alpha_c(\text{top}) = \frac{R_s \cdot D}{2\,P_{avg.}}\left(\frac{1}{2\pi}\right)^2 \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left[(\beta D)(\alpha D)\frac{A^{*h}}{D^2} - j(\omega\epsilon_1 D)\right.$$

$$\left.(\gamma_1 D)\frac{A^{*e}}{D^2}\right] \frac{w}{D}\left[\frac{\mathrm{Sin}\,(\alpha-\rho)\frac{w}{2}}{(\alpha-\rho)\frac{w}{2}}\right]$$

$$\left[-(\alpha D)(\beta D) \frac{A^h(\rho)}{D^2} + j(\omega \epsilon_1 D)(\gamma_1 D) \frac{A^e(\rho)}{D^2} \right]$$

$$d(\rho D) \quad d(\alpha D) \; . \tag{A-53}$$

Similarly,

$$\alpha_c^{(bottom)} = \frac{R_s}{2 \; P_{avg.}} \int_{-\infty}^{+\infty} f(x) \; H_{x2}(x,D) \; H^*_{x2}(x,D) \quad dx$$

$$= \frac{R_s}{2 \; P_{avg.}} \int_{-\infty}^{+\infty} f(x) \left(j\beta \frac{\partial \phi_2^h}{\partial x} + j\omega \epsilon_2 \frac{\partial \phi_2^e}{\partial y} \right)$$

$$\left(-j\beta \frac{\partial \phi_2^h}{\partial x} - j\omega \epsilon_2 \frac{\partial \phi_2^e}{\partial y} \right) dx \; . \tag{A-54}$$

Apply Parseval's theorem

$$\alpha_c^{(bottom)} = \frac{R_s}{2 \; P_{avg.}} \; \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Bigg(\left[j\beta \left(-j\alpha \Phi_2^h \right)^* + j\omega \epsilon_2 \frac{\partial \Phi_2^{*e}}{\partial y} \right]$$

$$\frac{1}{2\pi} \quad w \left[\frac{\operatorname{Sin} (\alpha - \rho) \frac{w}{2}}{(\alpha - \rho) \frac{w}{2}} \right] \left[-j\beta \left(-j\alpha \Phi_2^h \right) \right.$$

$$\left. - j\omega \epsilon_2 \frac{\partial \Phi_2^e}{\partial y} \right] \quad d\rho \Bigg) \quad d\alpha \tag{A-55}$$

or

$$\alpha_c^{(bottom)} = \frac{R_s}{2 \; P_{avg.}} \left(\frac{1}{2\pi} \right)^2 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \left[\beta \alpha \Phi_2^{*h} (\alpha) + j\omega \epsilon_2 \frac{\partial \Phi_2^{*e}(\alpha)}{\partial y} \right]$$

$$w \left[\frac{\operatorname{Sin}(\alpha - \rho) \frac{w}{2}}{(\alpha - \rho) \frac{w}{2}} \right] \left[-\beta \alpha \Phi_2^h(\rho) - j\omega \epsilon_2 \right.$$

$$\left.\frac{\partial \Phi_2^e(\rho)}{\partial y}\right] \quad d\rho \; d\alpha \; . \tag{A-56}$$

From the dispersion calculation [Ref. 6], at y=D

for $(\gamma_2 D)^2 > 0$, (γ_2 real) ,

$$\Phi_{2H}^h(\alpha, D) = C_H^h(\alpha) \; \text{Cosh} \; \gamma_2 D \tag{A-57}$$

$$\Phi_{2H}^e(\alpha, D) = B_H^e(\alpha) \; \text{Sinh} \; \gamma_2 D \tag{A-58}$$

$$\frac{\partial \Phi_{2H}^h(\alpha, D)}{\partial y} = \gamma_2 \; C_H^h(\alpha) \; \text{Sinh} \; \gamma_2 D \tag{A-59}$$

$$\frac{\partial \Phi_{2H}^e(\alpha, D)}{\partial y} = \gamma_2 \; B_H^e(\alpha) \; \text{Cosh} \; \gamma_2 D \tag{A-60}$$

and for $(\gamma_2 D)^2 < 0$, (γ_2 imaginary),

$$\Phi_{2T}^h(\alpha, D) = C_T^h(\alpha) \; \text{Cos} \; \gamma_2'' D \tag{A-61}$$

$$\Phi_{2T}^e(\alpha, D) = j \; B_T^e(\alpha) \; \text{Sin} \; \gamma_2'' D \tag{A-62}$$

$$\frac{\partial \Phi_2^h(\alpha, D)}{\partial y} = - \gamma_2'' \; C_T^h(\alpha) \; \text{Sin} \; \gamma_2'' D \tag{A-63}$$

$$\frac{\partial \Phi_{2T}^e(\alpha, D)}{\partial y} = j \gamma_2'' \; B_T^e(\alpha) \; \text{Cos} \; \gamma_2'' D \tag{A-64}$$

Substituting into equation (A-56),

$$\alpha_c^{(\text{Bottom})} = \frac{R_s}{2\,P_{avg.}} \left(\frac{1}{2\pi}\right)^2 \iint\limits_{\substack{\text{HYP.}\\ \text{REG.}}}{}_{-\infty}^{+\infty} \Big[\beta\alpha C_H^{*h}(\alpha)\ \text{Cosh}\ \gamma_2 D + j\omega\epsilon_2\gamma_2$$

$$\overset{*}{B}{}_H^{e}(\alpha)\ \text{Cosh}\ \gamma_2 D\Big]\ w \left[\frac{\text{Sin}(\alpha-\rho)\ \frac{w}{2}}{(\alpha-\rho)\ \frac{w}{2}}\right]$$

$$\Big[-\beta\alpha C_H^{h}(\rho)\ \text{Cosh}\ \gamma_2 D - j\omega\epsilon_2\gamma_2\ B_H^{e}(\rho)\ \text{Cosh}\ \gamma_2 D\Big]$$

$$d\rho\ d\alpha + \frac{R_s}{2\,P_{avg.}} \left(\frac{1}{2\pi}\right)^2$$

$$\iint\limits_{\substack{\text{TRIG.}\\ \text{REG.}}}{}_{-\infty}^{+\infty} \Big[\beta\alpha C_T^{*h}(\alpha)\ \text{Cos}\ \gamma_2'' D + \omega\epsilon_2\gamma_2''\ B_T^{*e}(\alpha)\ \text{Cos}\ \gamma_2'' D\Big]$$

$$w \left[\frac{\text{Sin}(\alpha-\rho)\ \frac{w}{2}}{(\alpha-\rho)\ \frac{w}{2}}\right] \Big[\beta\alpha C_T^{h}(\rho)\ \text{Cos}\ \gamma_2'' D$$

$$+ \omega\epsilon_2\gamma_2''\ B_T^{e}(\rho)\ \text{Cos}\ \gamma_2'' D\Big]\ d\rho\ d\alpha\,. \tag{A-65}$$

Putting equation (A-65) into normalized form,

$$\alpha_c^{(\text{Bottom})} = \frac{R_s \cdot D}{2\,P_{avg.}} \left(\frac{1}{2\pi}\right)^2 \iint\limits_{\substack{\text{HYP.}\\ \text{REG.}}}{}_{-\infty}^{+\infty} \Big[(\beta D)(\alpha D)\ \frac{C_H^{*h}(\alpha)}{D^2}$$

$$\operatorname{Cosh} \gamma_2 D \quad + j(\omega \epsilon_2 D)(\gamma_2 D) \frac{B_H^{*e}(\alpha)}{D^2} \operatorname{Cosh} \gamma_2 D \Big] \quad \frac{w}{D}$$

$$\left[\frac{\operatorname{Sin}(\alpha - \rho)\frac{w}{2}}{(\alpha - \rho)\frac{w}{2}}\right] \Big[-(\beta D)(\alpha D) \quad \frac{C_H^h(\rho)}{D^2} \operatorname{Cosh} \gamma_2 D$$

$$-j(\omega \epsilon_2 D)(\gamma_2 D) \quad \frac{B_H^e(\rho)}{D^2} \operatorname{Cosh} \gamma_2 D \Big] \quad d(\rho D) d(\alpha D)$$

$$+ \frac{R_s \cdot D}{2 P_{avg.}} \quad \frac{1}{2\pi}^{\,2} \quad \underset{\substack{\text{TRIG.}\\ \text{REG.}}}{} \quad \Big[(\beta D)(\alpha D)$$

$$\frac{C_T^{*h}(\alpha)}{D^2} \operatorname{Cos} \gamma_2'' D + (\omega \epsilon_2 D)(\gamma_2'' D) \quad \frac{B_T^{*e}(\alpha)}{D^2} \operatorname{Cos} \gamma_2'' D \Big]$$

$$\frac{w}{D} \quad \left[\frac{\operatorname{Sin}(\alpha - \rho)\frac{w}{2}}{(\alpha - \rho)\frac{w}{2}}\right] \Big[(\beta D)(\alpha D) \quad \frac{C_T^h(\rho)}{D^2}$$

$$\operatorname{Cos} \gamma_2'' D + (\omega \epsilon_2 D)(\gamma_2'' D) \quad \frac{B_T^e(\rho)}{D^2} \operatorname{Cos} \gamma_2'' D \Big]$$

$$d(\rho D) d(\alpha D) \quad . \tag{A-66}$$

APPENDIX B

COMPUTER PROGRAM

```
C     THIS PROGRAM IS DEVELOPED TO CALCULATE THE CHARACTE-
C     RISTIC IMPEDANCE AND LOSSES OF THE MICROSTRIP ON A DI-
C     ELECTRIC SUBSTRATE.
C     PROGRAM ACCEPTS FOLLOWING INPUT DATA
C     FIRST CARD-IDENTIFICATION DIGITS FORMAT (I3)
C     FIRST DIGIT    1   MEANS DIELECTRIC SUBSTRATE
C     FIRST DIGIT    2   MEANS FERRITE SUBSTRATE
C     SECOND DIGIT   1   MEANS SINGLE STRIP
C     SECOND DIGIT   2   MEANS COUPLE STRIP
C     THIRD DIGIT    1   MEANS EVEN MODE
C     THIRD DIGIT    2   MEANS ODD MODE
C     FOR LOSS CALCULATION THE FIRST CARD SHOULD BE 110
C     SECOND CARD-EPR1,EPR2,MR1,MR2      FORMAT(4F10.5)
C     EPR1-RELATIVE DIELECTRIC PERMITTIVITY IN REGION 1
C     EPR2-RELATIVE DIELECTRIC PERMITTIVITY IN REGION 2
C     MR1-RELATIVE MAGNETIC PERMEABILITY IN REGION 1
C     MR2-RELATIVE MAGNETIC PERMEABILITY IN REGION 2
C     THIRD CARD-DD,WW1,SS       FORMAT(3F10.5)
C     DD-THICKNESS OF THE SUBSTRATE (MILLIMETER)
C     WW1-WIDTH OF THE STRIP (MILLIMETER)
C     SS-SEPERATION BETWEEN STRIPS (MILLIMETERS)
C     FOURTH CARD-FREQH,MAXFREQ          FORMAT(2F10.5)
C     FREQ-INITIAL FREQUENCY  (GHZ.)
C     MAXFREQ-MAXIMUM INTERESTED FREQUENCY (GHZ.)
C     FIFTH CARD-CON      FORMAT(F10.5)
C     CON-CONDUCTIVITY OF THE STRIP
C     SIXTH CARD- TANL      FORMAT(F10.5)
C     TANL-LOSS TANGENT OF THE SUBSTRATE
      IMPLICIT REAL*8(A-H,K-Z)
      DIMENSION FYA(80), FYB(80), FYC(80), FYD(80), TRRA(2)
      DIMENSION YX(80), YY(80), YZ(80), YC(80), YF(80)
      DIMENSION TS1(2), TS2(2), TS3(2), TST(4)
      COMMON /FER/ PNS,IFSW
      COMMON /ZEYNEP/ S,IEO
      COMMON /ADA/ D,WOVD,WW
      COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
      COMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
      EXTERNAL GZR,GZIM
      EXTERNAL TORA,SULU
      EXTERNAL GEM,SAY
      EXTERNAL TUL,SIR
      DATA TS1/'DIELECTR',' FERRITE'/
      DATA TS2/'  SINGLE',' COUPLED'/
      DATA TS3/'   EVEN ','   ODD  '/
      READ(5,20)IDF,ISC,IEO
      READ(5,22)EPR1,EPR2,MR1,MR2
      READ(5,21)DD,WW1,SS
      READ(5,33)FREQGH,MAXFRE
```

```
      READ(5,36) CON
      READ(5,37) TANL
      KAK = DSQRT(EPR2)
      D = DD*1.D-3
      S = SS*1.D-3
      WW = WW1*1.D-3
      INIF = IDINT(FREQGH)
      IMF = IDINT(MAXFRE)
      IFRS = IDINT(.15/(KAK*D))
      IF (IMF.LT.IFRS) IFRS=IMF
      IFARK = IFRS-INIF+1
      IF (IFARK) 2,2,1
    1 ITIMES = IFARK
      GO TO 3
    2 WRITE (6,34)
      GO TO 19
    3 PI = 3.14159265358979D0
      PISQ = PI**2
      EPS = 0.1**1
      WOVD = WW/D
      FREQDD = FREQGH
C     SETTING LOWER AND UPPER LIMITS OF INTEGRATION
      BCB = -2.*PI/WW
      BBB = -BCB
      FREQGH = FREQDD
      WRITE (6,23) TS2(ISC),TS1(IDF)
      WRITE (6,26) WOVD
      IF (ISC.EQ.1) GO TO 4
      WRITE (6,27) WW1,SS,TS3(IEO)
      GO TO 5
    4 WRITE (6,24) WW1
    5 WRITE (6,25) EPR2,DD
      WRITE (6,28)
      WRITE (6,29)
      IF (ITIMES.GT.50) ITIMES=50
C
      DO 17 IS=1,ITIMES
      IFLG = 0
      IFSW = 0
      FREQ = FREQGH*1.E9
      LAM = 3.E8/FREQ
      DOVL = D/LAM
C     ROOT FINDING ROUTINE STARTS
C     USTL=UPPER LIMIT FOR  L/LPR
C     ALTL=LOWER LIMIT  FOR  L/LPR
      USTL = KAK-.01
      IF (IS-2) 6,7,7
    6 ALTL = (USTL+1.)/2.
```

```
      GC TO 8
    7 ALTL = LOVLPR
    8 LOVLPR = USTL
      ALTL1 = ALTL
      IA = 1
C     INTERMEDIATE  ALGEBRAIC  STEPS
    9 BETAD = 2.0*PI*DOVL*LOVLPR
      TA1 = 240.0*PISQ*DOVL
      TA = TA1*MR2
      TB1 = DOVL/60.0
      TB = TB1*EPR2
      TC = TA1*MR1
      TD = TB1*EPR1
      DCVLSQ = DOVL**2
      TE1 = LOVLPR**2
      TE2 = 4.0*PISQ*DOVLSQ
      TE = -TE2*(TE1-1.0)
      TF = TE2*(EPR2-TE1)
      FA2 = TE/TC
      FA3 = TF/TA
      FB1 = BETAD/TC
      FB2 = BETAD/TA
      FB9 = TE/TF
      FD1 = BETAD/TE
      FC1 = TD/TE
      FC2 = TB/TF
C     VALUES OF ALFA  WHERE  GAMMA 2  SWITCHES
C     REAL TO IMAGINARY
      ALF = DSQRT(TF/D**2)
      ALFN = -ALF
C     EVALUATION OF  INTEGRAL
      CALL DQG24 (BCB,ALFN,GZR,Y1)
      CALL DQG24 (ALFN,ALF,GZIM,Y2)
      CALL DQG24 (ALF,BBB,GZR,Y3)
      GZ = Y1+Y2+Y3
      IF (DABS(GZ).LT.EPS) GO TO 14
      IF (IA.NE.1) GO TO 10
      IA = 0
      LCVLPR = ALTL
      GZ1 = GZ
      GO TO 9
   10 IF (DABS(GZ1-GZ).GT.DABS(GZ1)) GO TO 12
      IF (ALTL.NE.ALTL1) GO TO 11
      ALTL = ALTL+0.001
      GC TO 13
   11 USTL = ALTL
      ALTL = (ALTL1+USTL)/2.
      LCVLPR = ALTL
```

```
      GZ1 = GZ
      GO TO 9
   12 ALTL1 = ALTL
   13 ALTL = (USTL+ALTL)/2.
      LCVLPR = ALTL
      GO TO 9
   14 AVR=DOVL
      YF(IS) = FREQGH
      IFLG = 1
C     EVALUATION OF INTEGRAL  FOR CHARACTERISTIC  IMPEDANCE.
      CALL DQG24 (BCB,ALFN,GZR,C1)
      CALL DQG24 (ALFN,ALF,GZIM,C2)
      CALL DQG24 (ALF,BBB,GZR,C3)
      CHIMP = (C1+C2+C3)*(1./(8.*PI**3))*D*2.0
      YC(IS) = CHIMP
      PAVE=CHIMP*PI**2
      RAD=(PI*FREQ*0.00000125)/CON
      RS=DSQRT(RAD)
      CALL DQG24 (BCB,ALFN,TORA,G1)
      CALL DQG24 (ALFN,ALF,SULU,G2)
      CALL DQG24 (ALF,BBB,TORA,G3)
      GPL1=(G1+G2+G3)*RS/PAVE
      GPL=8.68*GPL1/(2.*PI*100.)
      YY(IS)=GPL
      CALL DQG24 (BCB,ALFN,GEM,S1)
      CALL DQG24 (ALFN,ALF,SAY,S2)
      CALL DQG24 (ALF,BBB,GEM,S3)
      DRL1=((S1+S2+S3)*DOVL*EPR2*TANL*8.68)/(48000.*PI*PAVE)
      YZ(IS)=DRL1/2.
      CALL DQG24 (BCB,ALFN,TUL,T1)
      CALL DQG24 (ALFN,ALF,SIR,T2)
      CALL DQG24 (ALF,BBB,TUL,T3)
      CRL1=(T1+T2+T3)*RS*8.68/(PAVE*2.*PI*100.)
      YX(IS)=CRL1
   16 WRITE (6,30) YF(IS),YX(IS),YZ(IS),YY(IS),YC(IS)
      FREQGH = FREQGH+1.0D0
   17 CONTINUE
   19 CONTINUE
      STOP
   20 FORMAT (3I1)
   21 FORMAT (3F10.5)
   22 FORMAT (4F10.5)
   23 FORMAT ('1',//15X,'MICROSTRIP ANALYSIS'//15X,A8,2X,
     1 'STRIP'//15X,A8,2X,' SUBSTRATE'/)
   24 FORMAT ('0',15X,'WIDTH OF STRIP=',F5.3)
   25 FORMAT ('0',15X,'EPR2=',F5.1//16X,
     1 'THICKNESS D=',F5.3,2X,'MM'/)
   26 FORMAT ('0',15X,13(1H*)/2(16X,1H*,11X,1H*/),16X,1H*,
```

```
  1'W/D=',F4.1,3X,
  2  1H*/2(16X,1H*,11X,1H*/),16X,13(1H*)///)
27 FORMAT ('0',15X,'WIDTH OF STRIP=',F4.1,2X,'MM'//
  1 16X,'SEPERATION',F4.1,2X,'MM'//15X,A8,2X,'MODE')
28 FORMAT ('0',12X,'FREQUENCY ',2X,' CONDLOSS ',5X,
  1 'DLOSS',6X,'GLOSS',5X,'CH IMPEDANCE')
29 FORMAT (' ',10X,5(2X,10(1H_))//)
30 FORMAT ('0',12X,F6.3,1X,'GHZ',1X,E11.4,1X,
  1 E11.4,1X,E11.4,1X,F6.2,1X,'OHM'/)
31 FORMAT ('0',8X,'FREQUENCY',8X,'BF-/BPR ',10X,
  1 'BF+/BPR',10X,'2*PI*8.868*DELALFA/B **NEG AND POS')
32 FORMAT ('0',3X,F10.3,4(4X,F15.6))
33 FORMAT (2F10.5)
34 FORMAT ('0'//10X,'INITIAL FREQUENCY IS GREATER THAN'
  1 ,' ALLOWED MAXIMUM FREQUENCY SET BY THE PROGRAM TO',
  2 ' AVOID HIGHER ORDER MODES')
36 FORMAT(F10.0)
37 FORMAT(F10.8)
   END
   REAL FUNCTIONGZR*8(ALFA)
   IMPLICIT REAL*8(A-H,K-Z)
   DIMENSION T(400)
   COMMON /FER/ PNS,IFSW
   COMMON /ADA/ D,WOVD,WW
   COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
   COMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
   ALFAD = ALFA*D
   TG1 = ALFAD**2
   TG = TG1-TE
   VG = DSQRT(TG)
   BB = FB1*ALFAD/VG
   BC = FD1*ALFAD
   TH = TG1-TF
   VH = DSQRT(TH)
   FA1 = 1./DTANH(VH)
   BA = FA1*FB2*ALFAD/VH
   FFF1 = -(FA2/VG+FA3*FA1/VH)
   FFF2 = BB+BA
   FFF3 = -FFF2
   FFF4 = BC*(BB+BA*FB9)-(FC1*VG+FC2*FA1*VH)
   DENOM = FFF1*FFF4-FFF2*FFF3
   GG4 = -FFF1/DENOM
   GG2 = FFF2/DENOM
   GARA=DABS(ALFAD*WOVD*0.5)
   CALL BES(0,GARA,0,BJO,T,ERR)
   GX1=BJO
   GX=(PI*BJO)**2
   IF (IFLG.EQ.1) GO TO 1
```

```
      GZR = GG4*GX
      RETURN
    1 RCAA=GG4/TE
      RCAA1 = ALFAD*FD1*GG4
      RCAB = (1./(TC*VG))*(GG2-RCAA1)
      RRA = GX*RCAA**2
      RRB = GX*RCAB**2
      RCA = RCAA*RCAB*GX
      RCAC = GG4/(TF*DSINH(VH))
      RCAD = 1./(TA*VH*DSINH(VH))
      RCAE = -GG2+RCAA1*FB9
      RCB = RCAC*RCAD*RCAE*GX
      RRC = GX*RCAC**2
      RRD = GX*(RCAD*RCAE)**2
      P1B = ((TG1+TG)/VG)*(TD*RRA+TC*RRB)*BETAD
      P1C = 2.*ALFAD*(BETAD**2+TE2)*RCA
      P1INT = P1B+P1C
      RKA1 = DSINH(2.*VH)
      RKA = RKA1-(2.*VH)
      RKB = TG1*BETAD*TB*RRC/VH
      RKC = BETAD*TA*VH*RRD
      TAVTB = TE2*EPR2
      RKD = ALFAD*((TAVTB)+BETAD**2)*RCB
      RKE = RKB+RKC-RKD
      RKG = RKA1+(2.*VH)
      RKH = TG1*BETAD*TA*RRD/VH
      RKI = BETAD*TB*VH*RRC
      RKK = (TAVTB+BETAD**2)*ALFAD*RCB
      P2INT = RKA*RKE+RKG*(RKH+RKI-RKK)
      GZR = P1INT+P2INT*0.5
      RETURN
      END
      REAL FUNCTIONGZIM*8(ALFA)
      IMPLICIT REAL*8(A-H,K-Z)
      DIMENSION T(400)
      COMMON /FER/ PNS,IFSW
      COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
      COMMON /ADA/ D,WOVD,WW
      COMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
      ALFAD = ALFA*D
      TG1 = ALFAD**2
      TG = TG1-TE
      VG = DSQRT(TG)
      BB = FB1*ALFAD/VG
      BC = FD1*ALFAD
      TH = -TG1+TF
      VH = DSQRT(TH)
      FA1 = DCOTAN(VH)
```

```
      BA = FA1*FB2*ALFAD/VH
      FFF1 = -(FA2/VG-FA3*FA1/VH)
      FFF2 = BB-BA
      FFF3 = -FFF2
      FFF4 = BC*(BB-BA*FB9)-(FC1*VG+FC2*FA1*VH)
      DENOM = FFF1*FFF4-FFF2*FFF3
      GG4 = -FFF1/DENOM
      GG2 = FFF2/DENOM
      GARA=DABS(ALFAD*WOVD*0.5)
      CALL BES(0,GARA,0,BJO,T,ERR)
      GX1=BJO
      GX=(PI*BJO)**2
      IF (IFLG.EQ.1) GO TO 1
      GZIM = GG4*GX
      RETURN
    1 RCAA=GG4/TE
      RCAA1 = ALFAD*FD1*GG4
      RCAB = (1./(TC*VG))*(GG2-RCAA1)
      RRA = GX*RCAA**2
      RRB = GX*RCAB**2
      RCA = RCAA*RCAB*GX
      RCAC = GG4/(TF*DSIN(VH))
      RCAD = 1./(TA*VH*DSIN(VH))
      RCAE = GG2-RCAA1*FB9
      RCB = RCAC*RCAD*RCAE*GX
      RRC = GX*RCAC**2
      RRD = GX*(RCAD*RCAE)**2
      P1B = ((TG1+TG)/VG)*(TD*RRA+TC*RRB)*BETAD
      P1C = 2.*ALFAD*(BETAD**2+TE2)*RCA
      P1INT = P1B+P1C
      RKA1 = DSIN(2.*VH)
      RKA = 2.*VH-RKA1
      RKB = TG1*BETAD*TB*RRC/VH
      RKC = BETAD*TA*VH*RRD
      TAVTB = TE2*EPR2
      RKD = ALFAD*((TAVTB)+BETAD**2)*RCB
      RKE = RKB+RKC+RKD
      RKG = RKA1+(2.*VH)
      RKH = TG1*BETAD*TA*RRD/VH
      RKI = BETAD*TB*VH*RRC
      RKK = (TAVTB+BETAD**2)*ALFAD*RCB
      P2INT = RKA*RKE+RKG*(RKH+RKI-RKK)
      GZIM = P1INT+P2INT*0.5
      RETURN
      END
      REAL FUNCTIONTORA*8(ALFA)
      IMPLICIT REAL*8(A-H,K-Z)
      DIMENSION T(400)
```

```
COMMON /FER/ PNS,IFSW
COMMON /ADA/ D,WOVD,WW
COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
COMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
ALFAD = ALFA*D
TG1 = ALFAD**2
TG = TG1-TE
VG = DSQRT(TG)
BB = FB1*ALFAD/VG
BC = FD1*ALFAD
TH = TG1-TF
VH = DSQRT(TH)
FA1 = 1./DTANH(VH)
BA = FA1*FB2*ALFAD/VH
FFF1 = -(FA2/VG+FA3*FA1/VH)
FFF2 = BB+BA
FFF3 = -FFF2
FFF4 = BC*(BB+BA*FB9)-(FC1*VG+FC2*FA1*VH)
DENOM = FFF1*FFF4-FFF2*FFF3
GG4 = -FFF1/DENOM
GG2 = FFF2/DENOM
GARA=DABS(ALFAD*WOVD*0.5)
CALL BES(0,GARA,0,BJO,T,ERR)
GX1=BJO
GX=(PI*BJO)**2
RDAA1=ALFAD*FD1*GG4
RDAD=1./(TA*VH*DSINH(VH))
RDAE=-GG2+RDAA1*FB9
RDD=GX*(RDAD*RDAE)**2
RDAC=GG4/(TF*DSINH(VH))
RDC=GX*RDAC**2
RDB=RDAC*RDAD*RDAE*GX
RMZB=BETAD**2
RMZC=RMZA+TG1*RMZB
RMZD=RMZC*RDD
RMZE=TB**2
RMZF=RMZE*TH
RMZG=RDC*RMZF
RMZH=TB*ALFAD*BETAD*RDB*VH
TORA=RMZD+RMZG-2.*RMZH
RETURN
END
REAL FUNCTIONSULU*8(ALFA)
IMPLICIT REAL*8(A-H,K-Z)
DIMENSION T(400)
COMMON /FER/ PNS,IFSW
COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
COMMON /ADA/ D,WOVD,WW
```

```
CCMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
ALFAD = ALFA*D
TG1 = ALFAD**2
TG = TG1-TE
VG = DSQRT(TG)
BB = FB1*ALFAD/VG
BC = FC1*ALFAD
TH = -TG1+TF
VH = DSCRT(TH)
FA1 = DCOTAN(VH)
BA = FA1*FB2*ALFAD/VH
FFF1 = -(FA2/VG-FA3*FA1/VH)
FFF2 = BB-BA
FFF3 = -FFF2
FFF4 = BC*(BB-BA*FB9)-(FC1*VG+FC2*FA1*VH)
DENOM = FFF1*FFF4-FFF2*FFF3
GG4 = -FFF1/DENOM
GG2 = FFF2/DENOM
GARA=DABS(ALFAD*WOVD*0.5)
CALL BES(0,GARA,0,BJO,T,ERR)
GX1=BJO
GX=(PI*BJO)**2
RDAA1=ALFAD*FD1*GG4
RDAD=1./(TA*VH*DSIN(VH))
RDAE=GG2-RDAA1*FB9
RDD=GX*(RDAD*RDAE)**2
RDAC=GG4/(TF*DSIN(VH))
RDC=GX*RDAC**2
RDB=RDAC*RDAD*RDAE*GX
RMZA=TF**2
RMZB=BETAD**2
RMZC=RMZA+TG1*RMZB
RMZD=RMZC*RDD
RMZE=TB**2
RMZF=RMZE*TH
RMZG=RDC*RMZF
RMZH=TB*ALFAD*BETAD*RDB*VH
SULU=RMZD+RMZG-2.*RMZH
RETURN
END
REAL FUNCTIONGEM*8(ALFA)
IMPLICIT REAL*8(A-H,K-Z)
DIMENSION T(400)
CCMMON /FER/ PNS,IFSW
COMMON /ADA/ D,WOVD,WW
COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
COMMCN /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
ALFAD = ALFA*D
```

```
VG = DSQRT(TG)
BB = FB1*ALFAD/VG
BC = FD1*ALFAD
TH = TG1-TF
VH = DSQRT(TH)
FA1 = 1./DTANH(VH)
BA = FA1*FB2*ALFAD/VH
FFF1 = -(FA2/VG+FA3*FA1/VH)
FFF2 = BB+BA
FFF3 = -FFF2
FFF4 = BC*(BB+BA*FB9)-(FC1*VG+FC2*FA1*VH)
DENOM = FFF1*FFF4-FFF2*FFF3
GG4 = -FFF1/DENOM
GG2 = FFF2/DENOM
GARA=DABS(ALFAD*WOVD*0.5)
CALL BES(0,GARA,0,BJO,T,ERR)
GX1=BJO
GX=(PI*BJO)**2
RLA1=DSINH(2.*VH)
RLA=RLA1-(2.*VH)
REAA1=ALFAD*FD1*GG4
REAA=1./(TA*VH*DSINH(VH))
REAE=-GG2+REAA1*FB9
REE=GX*(REAA*REAE)**2
REAC=GG4/(TF*DSINH(VH))
REC=GX*REAC**2
REB=-REAC*REAA*REAE*GX
RLZA=TF**2
RLZB=BETAD**2
RLZC=(RLZB*TG1)+RLZA
RLZD=RLZC*REC/VH
RLZE=REE*VH*TA**2
RLZF=2.*TA*BETAD*ALFAD*REB
RLZG=(RLZD+RLZE+RLZF)*RLA
RLZH=TA**2
RLZI=REE*TG1*RLZH/VH
RLZK=RLZB*VH*REC
RLA2=RLA1+(2.*VH)
RLZL=RLA2*(RLZI+RLZK+RLZF)
GEM=RLZG+RLZL
RETURN
END
REAL FUNCTIONSAY*8(ALFA)
IMPLICIT REAL*8(A-H,K-Z)
DIMENSION T(400)
COMMON /FER/ PNS,IFSW
```

```
REAL FUNCTIONTUL*8(ALFA)
IMPLICIT REAL*8(A-H,K-Z)
DIMENSION T(400)
COMMON /FER/ PNS,IFSW
COMMON /ADA/ D,WOVD,WW
COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
COMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
ALFAD = ALFA*D
TG1 = ALFAD**2
TG = TG1-TE
VG = DSQRT(TG)
BB = FB1*ALFAD/VG
BC = FD1*ALFAD
TH = TG1-TF
VH = DSQRT(TH)
FA1 = 1./DTANH(VH)
BA = FA1*FB2*ALFAD/VH
FFF1 = -(FA2/VG+FA3*FA1/VH)
FFF2 = BB+BA
FFF3 = -FFF2
FFF4 = BC*(BB+BA*FB9)-(FC1*VG+FC2*FA1*VH)
DENOM = FFF1*FFF4-FFF2*FFF3
GG4 = -FFF1/DENOM
GG2 = FFF2/DENOM
GARA=DABS(ALFAD*WOVD*0.5)
CALL BES(0,GARA,0,BJO,T,ERR)
GX1=BJO
GX=(PI*BJO)**2
ALAA=(1./(TC*VG))**2
ALAB=(GG2-BC*GG4)**2
ALAC=GX*ALAB*ALAA
ALAD=GX*(GG4/TE)**2
ALAE=(GG4/TE)*(1./(TC*VG))
ALAF=ALAE*(GG2-(BC*GG4))*GX
ALAG=1./(TA*VH)
ALAH=-GG2+BC*FB9*GG4
ALAK=ALAG**2
ALAL=ALAH**2
ALAM=ALAK*ALAL*GX
ALAN=((GG4/TF)**2)*GX
ALAO=ALAG*ALAH*GX*(GG4/TF)
ALAP=ALAC*TG1*BETAD**2
ALAR=2.*TD*ALFAD*BETAD*VG*ALAF
ALAS=TG*ALAD*(TD)**2
ALAT=BETAD**2
ALAU=ALAM*ALAT*TG1
ALAV=2.*TB*BETAD*ALFAD*VH*ALAO
ALAY=TB**2
```

```
ALAZ=ALAY*TH*ALAN
ALBA=DCOSH(2.*VH)+1.
ALBB=DCOSH(2.*VH)-1.
ALBC=ALBA/ALBB
ALBD=ALBC*(ALAU-ALAV+ALAZ)
ALBE=ALAP+ALAR+ALAS
TUL=ALBD+ALBE
RETURN
END
REAL FUNCTIONSIR*8(ALFA)
IMPLICIT REAL*8(A-H,K-Z)
DIMENSION T(400)
COMMON /FER/ PNS,IFSW
COMMON /AT/ TA,TB,TC,TD,PI,BETAD,TE2,EPR2,IFLG
COMMON /ADA/ D,WOVD,WW
COMMON /EMRE/ TE,TF,FA2,FA3,FB1,FB2,FB9,FC1,FC2,FD1
ALFAD = ALFA*D
TG1 = ALFAD**2
TG = TG1-TE
VG = DSQRT(TG)
BB = FB1*ALFAD/VG
BC = FD1*ALFAD
TH = -TG1+TE
VH = DSQRT(TH)
FA1 = DCOTAN(VH)
BA = FA1*FB2*ALFAD/VH
FFF1 = -(FA2/VG-FA3*FA1/VH)
FFF2 = BB-BA
FFF3 = -FFF2
FFF4 = BC*(BB-BA*FB9)-(FC1*VG+FC2*FA1*VH)
DENOM = FFF1*FFF4-FFF2*FFF3
GG4 = -FFF1/DENOM
GG2 = FFF2/DENOM
GARA=DABS(ALFAD*WOVD*0.5)
CALL BES(0,GARA,0,BJO,T,ERR)
GX1=BJO
GX=(PI*BJO)**2
ALAA=(1./(TC*VG))**2
ALAB=(GG2-BC*GG4)**2
ALAC=GX*ALAB*ALAA
ALAD=GX*(GG4/TE)**2
ALAE=(GG4/TE)*(1./(TC*VG))
ALAF=ALAE*(GG2-(BC*GG4))*GX
ALAG=1./(TA*VH)
ALAH=-GG2+BC*FB9*GG4
ALAK=ALAG**2
ALAL=ALAH**2
ALAM=ALAK*ALAL*GX
```

```
      ALAN=((GG4/TF)**2)*GX
      ALAO=ALAG*(GG2-(BC*FB9*GG4))*GX*(GG4/TF)
      ALAP=ALAC*TG1*BETAD**2
      ALAR=2.*TD*ALFAD*BETAD*VG*ALAF
      ALAS=TG*ALAD*(TD)**2
      ALAT=BETAD**2
      ALAU=ALAM*ALAT*TG1
      ALAV=2.*TB*BETAD*ALFAD*VH*ALAO
      ALAY=TB**2
      ALAZ=ALAY*TH*ALAN
      ALBA=1.+DCOS(2.*VH)
      ALBB=1.-DCOS(2.*VH)
      ALBC=ALBA/ALBB
      ALBD=ALBC*(ALAU-ALAV+ALAZ)
      ALBE=ALAP+ALAR+ALAS
      SIR=ALBD+ALBE
      RETURN
      END
C     SUBROUTINE  DQG24  STANDART IBM ROUTINE
      SUBROUTINE DQG24 (XL,XU,FCT,Y)
      DOUBLE PRECISION XL,XU,Y,A,B,C,FCT
      A=.5D0*(XU+XL)
      B=XU-XL
      C=.4975936099985107D0*B
      Y=.6170614899993599D-2*(FCT(A+C)+FCT(A-C))
      C=.4873642779856547D0*B
      Y=Y+.1426569431446683D-1*(FCT(A+C)+FCT(A-C))
      C=.4691372760013664D0*B
      Y=Y+.2213871940870990D-1*(FCT(A+C)+FCT(A-C))
      C=.4432077635022005D0*B
      Y=Y+.2964929245771839D-1*(FCT(A+C)+FCT(A-C))
      C=.4100009929869515D0*B
      Y=Y+.3667324070554015D-1*(FCT(A+C)+FCT(A-C))
      C=.3700620957892772D0*B
      Y=Y+.4309508076597664D-1*(FCT(A+C)+FCT(A-C))
      C=.3240468259684878D0*B
      Y=Y+.4880932605205694D-1*(FCT(A+C)+FCT(A-C))
      C=.2727107356944198D0*B
      Y=Y+.5372213505798282D-1*(FCT(A+C)+FCT(A-C))
      C=.2168967538130226D0*B
      Y=Y+.5775283402686280D-1*(FCT(A+C)+FCT(A-C))
      C=.1575213398480817D0*B
      Y=Y+.6083523646390170D-1*(FCT(A+C)+FCT(A-C))
      C=.9555943373680815D-1*B
      Y=Y+.6291872817341415D-1*(FCT(A+C)+FCT(A-C))
      C=.3202844643130281D-1*B
      Y=B*(Y+.6396909767337608D-1*(FCT(A+C)+FCT(A-C)))
      RETURN
```

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c.1 Microstrip loss.